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Lane, B. H., 1935. Suggestions to authors of papers submitted for publication by the United States Geological Survey: U. S. Geol. Survey, Washington, D. C. (For sale by Superintendent of Documents, Washington, D. C., 25c.)

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THE STAGES OF LAKE CHICAGO: THEIR CAUSES AND CORRELATIONS

J HARLEN BRETZ

ABSTRACT. The three named stages of Glacial Lake Chicago record 1) the earliest static lake level (Glenwood), 2) a time of rapid lowering because of outlet deepening, 3) a pause in this deepening and lowering to produce the second static stage (Calumet), 4) renewed lowering because of renewed outlet deepening, and 5) a final level (Toleston) determined by a bed rock sill in the outlet channel floor. The dam for the lake was not the Valparaiso moraine but the younger Tinley moraine and its valley train. No stoping by retreat of rapids was involved in outlet deepening. The thesis of this paper is that the outlet down-cuttings (items 2 and 4) are to be correlated with times when glacial lakes in the Erie and Huron basins discharged into Lake Chicago and thus added to the erosive ability of its outlet river; the two earlier static water levels (items 1 and 3) with times when these eastern lakes discharged elsewhere. Deposition of the Valders red drift of the northern Lake Michigan basin (Early Mankato) is thought to have been contemporaneous with the intermediate stage of Lake Chicago. The Port Huron moraine is believed to be of late Cary age and, in earlier studies, to have been incorrectly correlated across Lake Michigan.

GENERAL STATEMENT

Glacial Lake Chicago existed in the Lake Michigan basin in front of a retreating lobe of the Wisconsin ice sheet and discharged to the Illinois River, an affluent of the Mississippi. Its three groups of shore lines record three different stages of essentially static level, separated by two stages of relatively rapid lowering from one level to another. With only one exception, all who have studied the lake's history consider that the highest stage was the earliest and the lowest the latest, that each static stage was determined by minimum erosion on the channel floor at the head of the outlet, and that each drop in lake level was caused by fairly rapid deepening at the channel head.

The landward margin of Lake Chicago was the Valparaiso moraine system which loops around the southern end of the basin in the familiar Wisconsin lobate habit (fig. 1). Two

low places in this moraine became simultaneous discharge ways, converging to become one a few miles down stream. Both continued to function during nearly forty feet of deepening from the highest (Glenwood) to the lowest (Toleston) stage of the lake. The intermediate (Calumet) shore line lies approximately in the middle of this vertical interval.

EARLIER EXPLANATIONS OF THE LAKE STAGES

Leverett, who named the lake (1897, p. 65), did not propose any specific explanation for the pauses which interrupted the down-cutting of the outlet.

Alden (1902, p. 7) suggested that an unrecorded pre-Glenwood stage was lowered to the Glenwood level by erosional deepening of the outlet. At this level, the outlet river

> ". . . found its channel resting upon rather resistant drift and rock from the head of the outlet nearly across the whole breadth of the obstructing moraine, while on the outside of the moraine there was a sharp descent. As a result there was for a period, very little cutting at the entrance of the outlet, while there was comparatively swift cutting at the rapids formed on the outer side of the moraine. These rapids gradually cut back . . . [until they] . . . had traversed the breadth of the moraine and reached the head of the outlet. Immediately on doing this, the waters would be rapidly drawn off to a level [Calumet intermediate stage] represented by the foot of the stope thus carried from the outer to the inner side of the obstructing moraine."

Alden credited T. C. Chamberlin with this idea of stoping to explain the abrupt lowering of Lake Chicago, but applied it only to the drop from the Glenwood to the Calumet level and said nothing in explanation of the next lowering, from Calumet to Toleston levels.

Goldthwait (1909, pp. 52-55) proposed a modified stoping hypothesis, his idea being that the valley train west of the Valparaiso moraine served, with the moraine, as a dam for the Glenwood stage, that trenching of this dam caused the lowering, and that discovery of a bed-rock sill determined the Calumet level. Down the far side of this sill (at Lockport) was a rapids which, by stoping, receded eastward up the valley. It eventually cut completely through the sill and abruptly

terminated the Calumet intermediate stage and introduced the lowest or Toleston stage.

Wright (1918, pp. 235-244) accepting the idea of stoping, visualized rapids whose vertical descent was the full interval between the highest and lowest shore lines. Lake Chicago, by his view, dropped from the Glenwood immediately to the Toleston level. Only glacial deposits were removed in the stoping, and the bed rock beneath stopped all further deepening. To account for the intermediate Calumet level, Wright had recourse to a known great influx of water from the east. The volume added to Lake Chicago was so great that the outlet river rose twenty feet and so remained during the Calumet stage.

There are deficiencies or internal disharmonies or conflicts with field evidence in each of these hypotheses. Alden's mechanism provides only for a drop from the highest to the intermediate lake stage, offers no explanation for the Calumet pause and the ensuing comparable drop to the Toleston level. Goldthwait's scheme is faulty in providing no abrupt drop, only a gradual lowering, from the highest to the intermediate shore line. Field evidence is to the contrary and it also includes glacial striae on the rock floor at Lemont. Wright's concept demands an enormous volume of water from the east and a long stand of the lake at the Calumet level. Even if the outlet floor was on bed rock, the walls were in drift and widening of the channel would seemingly have been inevitable. The lake, if flooded as Wright saw it, would by this widening have been gradually lowered from an initial and short-lived Calumet level back down to the earlier Toleston. The absence of minor shore lines on the lake plain, between the three already named, clearly testifies to two rather abrupt lowerings.

The three proposed explanations are defective in their lack of specific supporting field data. The writers did not neglect evidence then known, but they theorized on too slender an accumulation of facts. It was only after a detailed study of the Chicago region was undertaken for the Illinois State Geological Survey that information vital to the solution of the problem came to light. The explanation presented in this paper is still theoretical, but it takes account of much knowledge these earlier students did not possess. Most significant has been a reinterpretation of the character of the morainic belt

crossed by the outlet channels. Essential also has been the advance in knowledge of glacial lake stages in the Huron and Erie basins, contemporaneous with those in the Michigan basin.

NEW FIELD DATA AND THEIR SIGNIFICANCE

The Valparaiso morainic upland where crossed by the Lake Chicago outlet channels has proved to be composed largely of a silty, pre-Valparaiso drift (Bretz, 1939, p. 53) with a relief as well as a thickness considerably exceeding that of the overlying clayey Valparaiso till. The relief of the older drift is largely due to later but pre-Valparaiso stream erosion, the valleys only slightly obscured by the younger Valparaiso mantle.

A dozen or more of these partially obstructed pre-Valparaiso valleys are readily recognizable in the Chicago region and others have been identified farther north (Powers and Ekblaw, 1940, pp. 1329-1336). Two of them, converging to become one, were utilized by the Lake Chicago outlets. They provided the two low places which, by earlier students, had been ascribed simply to irregularities in moraine deposition. Their floors were on bed rock in places and surviving glacial straie, on these floors (Leighton and Ekblaw, 1932) testify that no rapids in the outlet river ever retreated by stoping in bedrock along the trans-morainic channels. Esker and kame deposits, built on the slopes of both valleys during Valparaiso retreat, extend down almost to the present floors. The outlet channels of Lake Chicago therefore were not notably eroded by discharging lake water after the building of the Valparaiso moraine. They were, for the most part, as deep before that drift was deposited as they are today.

But before one concludes that volume of discharge alone could have determined the water level at outlet heads, and therefore the different lake levels, another significant feature of the outlet region must be considered. That feature is a definite moraine ridge, younger than the Valparaiso moraine and built up on its eastern slope. This Tinley moraine appears to record a readvance of the Lake Michigan lobe after a considerable retreat eastward from the Valparaiso moraine. Earlier students of the region failed to recognize 1) the Tinley moraine as distinctly younger than the Valparaiso moraine belt and 2)

the pre-Valparaiso age of the valleys which became the outlet channels.

During this retreat from the Valparaiso and readvance to the Tinley moraine, meltwater and probably glacial-lake water escaped down the two trans-morainic valleys. Any minor moraine obstructions left in them by the Valparaiso ice were largely removed and free drainage was established along their floors at about the level of the future Toleston stage.

This conclusion is established from the relations of Tinley moraine and outwash to the valleys in question. The Tinley ice barely more than reached the outlet-valley heads but it built a morainic dam across each and its outwash built a valley train in each. In the Sag Valley, the southern of the two, a terrace fragment of valley train, extensively excavated and exposed just west of the moraine, is composed of poorly sorted, irregularly bedded gravel which has depositional dips away from the moraine, and contains numerous till balls and pebbles and large, irregular masses of till intimately associated with ice-thrust deformations. Although there are other gravels along these outlet valleys, not related to the Tinley moraine, the composition and structure of this deposit differ so notably from them that not alone the writer but other contemporary students of the region, including M. M. Leighton and G. E. Ekblaw of the Illinois State Geological Survey, are convinced that the terrace is a remnant of a once-continuous Tinley valley train in Sag Valley.

The northern trans-morainic valley (Desplaines) must have been similarly blocked by moraine and outwash, else it alone would have functioned during the Lake Chicago history. The two dams must have been of comparable height and bulk for whatever the conditions that caused the three lake stages, they obtained in both channels throughout all stages.

The terrace remnant of Tinley outwash is at least 20 feet thick, its lowest exposure 610 feet A.T., only 10 feet higher than the Toleston level of the lake. Thus it is clear that an open valley whose floor was as low as 610 feet drained westward through the Valparaiso moraine at the time the Tinley moraine was built. The surface of the deposit is close to 630 feet A. T., 10 feet lower than the Glenwood level of Lake Chicago. The crest of the surviving buttress of the moraine itself is 685 feet A. T. Discharge from incipient Lake Chicago,

spilling 40 or 50 feet down over the face of this moraine, must have rapidly eroded a channel down to the surface of the valley train which surely extended several miles down valley. The much thicker dam and much gentler gradient thus encountered were prime factors in determining the 635-640 Glenwood level. The same interpretation must be applied to the northern or Desplaines channel also, although no good field evidence for a Tinley valley train has yet been found in it.

Another field item in the problem is the occurrence of great numbers of boulders on several remnants of current-swept channel floor of all three lake stages. Both Leverett (1899, p. 426) and Alden (1902, p. 7) estimated a thousand to the acre showing at the surface in one tract at the head of the Sag; the writer would make the same estimate for a tract in the Desplaines channel head. These boulder fields seem clearly to be lag deposits from erosion of the till during channel deepening. Their significance is pointed out in a following paragraph.

CAUSES OF THE LAKE CHICAGO STAGES

The Tinley drift dams in both outlets were destroyed during the life of Lake Chicago. There is nothing in the composition or structure of the remaining abutments of these dams to suggest that two long pauses in their erosion should have occurred, as they did, to determine the Glenwood and Calumet stages or, expressed differently, that two times of accelerated erosion should have occurred to lower the lake about 20 feet each time. Though the Tinley dam held Lake Chicago to all levels above the Toleston, the cause of the deepening which produced the two marked lowerings seems not to be found in the outlet region. It is believed to lie far to the east of Lake Chicago; to have been determined by events in the life of contemporaneous great glacial lakes in front of the Erie and Huron lobes (Leverett and Taylor, 1915). The complicated history of those lake levels can be presented only in outline here. For a time, these eastern lakes discharged across Michigan into Lake Chicago, greatly augmenting the volume previously escaping through its outlets. Later, retreat of the Huron and Erie lobes exposed a lower spillway to the Mohawk, and Lake Chicago's discharge shrank accordingly. A still later readvance closed the eastern outlet and overflow again was turned into Lake Chicago.

If widths of the Chicago outlet channels did not notably increase during these times of increased discharge (and field evidence seems to indicate this), then depth of water in the channels must have become greater. When a stream's volume is increased without change in load, in channel shape and roughness, and in gradient, there results an increase in velocity. Doubling the discharge, with other factors unchanged, may produce as much as a 20 per cent increase in velocity.[1] Since the erosive ability of running water varies with the square of the velocity, a small increase in velocity might produce a noteworthy increase in a stream's erosive work, particularly if it is flowing on unconsolidated material. Doubling the discharge from Lake Chicago by introduction of Erie and Huron glacial water is well within the limits of probability.

Channel-deepening in glacial till when only Lake Chicago water was using the outlets would yield an increasing number of lag boulders on the floor. Finally an armor of big fragments could bring deepening essentially to an end. Only a marked increase in erosive ability of the outlet rivers could clear the channel floors and allow more deepening. These two opposed conditions: decreased erosion from accumulation of boulder pavements, and increased erosion from increased velocity, are here considered to have alternated during Lake Chicago's history. Each of the two earlier stages was determined by collection of a channel-bottom armor of fragments too large for the outlet river to remove. Each of the two times of rapid lowering was determined by large influx of water from the east, increased erosional and transportational ability in the outlets, and a consequent sweeping away of the boulders and a cutting into the Tinley till and outwash beneath.

CORRELATIONS WITH GLACIAL LAKES IN THE HURON AND ERIE BASINS

The Glenwood shore line, as noted by both Alden and Goldthwait, is not a single, simple feature. Its deposits range through approximately 10 feet vertically and its wave-cut cliff bases are generally several feet lower than the highest deposits. Part of this may well be due to variation in storm-wave work on differently exposed coasts, part is probably a

[1] Dr. H. A. Einstein, personal communication.

record of lowering lake level because of slight deepening in the outlet channels. But growth of boulder pavements during the earliest of Lake Chicago's existence is here considered to have brought about an end of this deepening and an essential stabilizing of the Glenwood lake level.

Then, without leaving any surviving shore lines, Lake Chicago rather abruptly dropped to the Calumet level as the large volume of water poured into it via Grand River, Michigan, from the eastern glacial lakes, middle and late Maumee, Saginaw, Arkona and Whittlesey, was added to its outlet rivers.

The latest of these lake stages, Lowest Arkona, was terminated when the northeastward retreating front of the Erie lobe exposed an escapeway lower than Grand River, near Syracuse, New York. The lowered lake, in the Erie and Huron basins, Lake Wayne, drained to the Mohawk and during such time the Chicago outlet again carried only Lake Chicago water. Decreased volume, much decreased velocity and a boulder-covered floor inherited from the previous stage decreed a cessation of the deepening which had been lowering Lake Chicago since Glenwood time. In the simple analysis now being outlined, this constituted the pause at the Calumet level.

A readvance of the Huron-Erie ice lobe then occurred, closing the Mohawk spillway, raising the water level back to the Grand River outlet across southern Michigan and discharging the new eastern lake, (Warren), into Lake Chicago. Renewed erosion in the Chicago outlet channels which ensued caused the lowering from the Calumet to the Toleston level. This time of erosion saw both channels cut down to bed rock, after

Tabulated, the correlation is as follows:

Huron and Erie Basins	*Michigan Basin*
Early Lake Maumee, discharging to Wabash River	Glenwood stage
Middle and late Lake Maumee, Lakes Saginaw, Arkona and Whittlesey, discharging to Lake Chicago	Lowering from Glenwood to Calumet level
Lake Wayne, discharging to Mohawk River	Calumet stage
Lake Warren, discharging to Lake Chicago	Lowering from Calumet to Toleston level
Lake Lundy (Dana), discharging to Mohawk River, and all later stages to Lake Algonquin	Toleston stage

which rapid deepening in the now low-gradient outlet ceased on the resistant substratum.[2]

Perhaps the most questionable element in this correlation of the Lake Chicago stages with the lake succession in the Huron and Erie basins is the assignment of most of Maumee's history and all of Arkona's and Whittlesey's to the first down-cutting interval, during which Lake Chicago left no recognizable shore lines. The relative duration of any glacial lake in the list, or of any stage of any lake, can at present be judged only from the development of its shore line. This is an unsatisfactory criterion because several factors other than duration influenced the result, and they varied from place to place and from time to time.

One principle that must be recognized in evaluating the duration of any lake stage by the bulk of its beach deposits is that the shore built at the close of a rising interval will be stronger than one made at the end of an interval of lowering, time and other factors being the same. This is because, during the rise, waves are constantly sweeping beach materials before them in one cumulative aggregate. During a subsidence of water level, beach materials are likely to be left behind as thin deposits spread widely over the abandoned territory. Lake Warren was such a rising stage.

Warren also was a larger lake than any predecessor and had a much longer contributing ice front. It must have discharged a correspondingly greater volume.[3]

For the sake of clarity in presenting the above principles and correlation, a feature of glacial lake history in the Lake Michigan basin has thus far been omitted. It is the occurrence of low-water stages, lower than the Toleston, at times when the ice front withdrew entirely from the Huron and Erie basins, lower outlets were discovered and the western channels went dry. In one of these stages, the lake plain emerged almost

[2] A low-water stage in the Erie basin, following Lake Warren but preceding the later Lake Lundy, is argued by Bay (1936). Since, by the view here urged, the Chicago outlets had already been deepened to bed rock, the occurrence of this "second Lake Wayne" in no way affects the proposed correlation.

[3] Fluctuations in the volume of eastern contributions, both before and after the Lake Wayne stage, which are argued for elsewhere (Bretz, in press), appear to have been fractions of Lake Chicago's total discharge, too small to have affected its outlet channel as they did the Saginaw Basin outlet.

as completely as it stands today (Baker, 1920) and much more extensively in another (Stanley, 1938). The location of the outlets of these low-water stages must have been well toward the north end of the Michigan basin and may have been the strait at Mackinac. For their functioning, similar low channels eastward out of the Huron basin also must have existed, channels now completely buried in drift.

The earliest and perhaps best established of the low-water stages was the Bowmanville (Baker, 1920) occurring between the Glenwood and Calumet high-water stages. To make a place for the Bowmanville stage, the sequence above proposed would be amended as follows:

1. Glenwood stage. After a prompt notching of the narrow Tinley moraine dam down to the level of the wider dam provided by the Tinley valley train, the lower gradient of that outwash plus an accumulation of channel floor boulders held Lake Chicago to a fairly constant level while the series of Glenwood beaches was built.

2. Contributions from middle and late Maumee began[4] and continued from its successors, lakes Arkona and Whittlesey. Discharge across the Tinley dam thus was at least doubled, and the increased velocity caused the erosion by which it became lowered to the first-attained Calumet level.

3. A marked retreat of the Michigan, Huron and Erie lobes opened some eastward discharge route. This produced the Bowmanville low-water stage when the Chicago outlet went dry.

[4] The reader who may consult Monograph 53, U. S. Geol. Survey, should be warned that plate XIV is too generalized to agree with the detailed text of either Leverett or Taylor. Taylor (pp. 260-261) says that the Grand River channel, carrying glacial-lake water westward across Michigan "at first" reached Lake Chicago west of Grand Rapids at an altitude of about 640 feet. On p. 360, "first" is defined as Lake Maumee discharge before Lake Saginaw had begun to be formed. Leverett (pp. 220, 225 and 227) describes glacial drainage channels leading south from Grand Rapids to "incipient" Lake Chicago, south of the Indiana line. This drainage had to cross a col at about 700 feet and these channels operated only when the ice stood on the Lake Border moraines, thus completely filling that part of the basin now occupied by Lake Michigan. Although the generalized map (plate XIV) shows a continuous glacial river from Lake Saginaw to incipient Lake Chicago, there are really two different channels of two different ages. The discharge southward along the eastern edge of the Lake Michigan lobe antedated the first lake discharge westward across Michigan and when the later river flowed, Lake Chicago water reached as far north as Grand Rapids.

Record of this retreat has been found, to date, only in the Lake Michigan basin although the episode must have been shared by the eastern basins.

4. Readvance of the lobes, closure of the low outlet to the east, rise of glacial lake water in all eastern basins to the Mohawk outlet level, giving origin to Lake Wayne. Concomitant rise of Lake Chicago back to the Calumet level, the waves of this rising stage sweeping beach materials forward and upward on the gentle slopes being submerged until westward discharge was again established. Thus the Calumet shore line was completed. The Calumet beach therefore is dated as later than the cutting down of the outlets to the same level.[5]

5. Further readvance of ice in the Huron and Erie basins closed the Mohawk outlet, produced Lake Warren and turned its discharge into Lake Chicago.

6. This increased discharge renewed erosional deepening in Lake Chicago's outlet channels and the lake fell from the Calumet to the Toleston level, too rapidly and too uniformly to leave minor intervening shores. The outlet channels then encountering bed rock, no further deepening occurred, whatever the volume of discharge.

Another factor which may have entered into the complex of causes for the glacial lake history was the differential uplift that occurred during the changing scenes of the glacial lakes. North of the "hinge lines," all glacial lake shore lines rise toward the northeast, the oldest ones most, the youngest ones least. It is possible that the Bowmanville low-water stage was terminated and the level of Lake Chicago raised 30 feet at the south end of the basin because of uplift, at this time, of the eastern or northeastern region where the Bowmanville outlet existed. A slow rise in lake level caused in this way would be more likely to drive the beach materials forward instead of submerging them, than would the more rapid rise caused by an ice readvance (item 4 above). Probably, however, the uplift

[5] If the origin of the Calumet shore line is correctly explained here, it must be limited to beach ridges built on gently sloping tracts where the proposed mechanism could operate. Calumet wave-cut cliffs would be possible only if considerable time elapsed after Lake Chicago rose to the level of the abandoned outlet but before Lake Warren discharge arrived. It seems significant that no cliffed Calumet shoreline is described in the literature although both Glenwood and Toleston shores have cliffs.

was too slow to have consummated this before readvance of the lobes produced the same effect on the lake.

EARLIER CORRELATIONS OF MORAINES ACROSS THE LAKE MICHIGAN BASIN

The Port Huron moraine in Michigan (fig. 1.) was built by the advance which gave rise to Lake Whittlesey. This moraine has been presumed by all previous students to be of the same age as the red drift bordering the northern half of the west side of Lake Michigan and considered by Leighton (1931), following Leverett (1929), to be earliest Mankato. But new evidence shows that before a marker among the events of Lake Chicago's history is selected as the beginning of the Mankato subage, these correlations must be critically examined.

Leverett and Taylor (1915, p. 302) described the course of the Port Huron morainic system (the Lake Whittlesey stage) from its type locality (south end of Lake Huron) northward and westward around the Saginaw lobe, thence northward along a great reentrant loop in the southern peninsula of Michigan and back southward to the shore of Lake Michigan near Muskegon. Here it was supposedly cut off by the lake shore in about the same latitude in which, on the east, it extends south of Lake Huron into Ontario. Leverett correlated this Port Huron moraine with the sheet of red drift which on the west side of Lake Michigan extends as far south as Milwaukee. The red drift is only mildly morainic, however, as compared with the Michigan phase of the supposed same drift.

Alden (1918) believed the red color of the drift north of Milwaukee was due to plowing up of slightly older lake clays which contained a sufficiently high proportion of debris from iron-rich rocks of the Lake Superior region. He accepted Leverett's moraine correlation across Lake Michigan from Muskegon to Milwaukee but was puzzled by the fact that Leverett did not report the Muskegon moraine as red drift; did not report a red till moraine anywhere on the east side of Lake Michigan south of Manistee, 65 miles north of Muskegon. Because, however, the Port Huron moraines run almost parallel to the lake shore from Muskegon to Manistee, this is no great gap when measured across the trend of the ridges. Alden correlated the Manistee moraine with a ridge along the Wisconsin shore at Two Rivers, about 15 miles back from the extreme

western edge of the red drift and almost directly across from Manistee.

In 1929, Leverett added to his mapping of the edge of the Port Huron drift in Wisconsin, Minnesota and Iowa, correlating the Des Moines lobe west of the Mississippi with the red drift north of Milwaukee and of the Port Huron system in Michigan.

In 1931, Leighton followed Leverett's correlation in proposing a terminology for the different Wisconsin sub-stages. Although he changed the proposed nomenclature two years later (1933), using Mankato, Minnesota, as the type locality for the drift of the sub-stage we are considering, he accepted Leverett's correlation as before.

Thwaites in 1937 subdivided Mankato drift into Early (red drift) and Later (Des Moines lobe west of the Mississippi) but he also followed Leverett's correlation across Lake Michigan and considered the Port Huron moraine to be Early Mankato. Thwaites discovered that the red drift of Wisconsin west of Lake Winnebago, Green Bay and Menominee River is a very thin till sheet and has no end moraines. In 1943, he announced that the mildly morainic topography of the red drift of his area is that of Cary moraines buried by the thin red (Valders) till.[6] He reasserted the lack of moraine topography in the red drift itself and thought that only a very brief advance was recorded by it. He doubted the trustworthiness of a correlation of the Wisconsin red drift with the Des Moines-Mankato drift of Iowa and Minnesota because "so vast an expanse of unsettled, little-known territory" lay between.

Although probably most workers consider the correlation of moraines across the Lake Michigan basin an uncertain procedure, they have depended on four criteria for what they have suggested or accepted: 1) the color contrast between gray till in the southern part of the basin and red till to the north, 2) the relationship of the Lake Border moraines which are traceable on land around the lake's southern end, 3) the assumption of approximate symmetry of the ice-lobe front in the open glacial lake, and 4) a belt of somewhat lesser depths of the modern lake between Muskegon and Milwaukee, supposedly the submerged Port Huron moraine.

[6] Alden (1918) reported two places where ice depositing the red drift had overridden older moraines.

Since Thwaites' discovery that the Valders red drift of his area has no moraines of its own, doubt must rise that this thin till can be the equivalent of the strongly developed Port Huron morainic system just across the lake. If the shallower belt of Lake Michigan between Muskegon and Milwaukee is the submerged massive Port Huron moraine, it should not abruptly flatten out on emergence near Milwaukee. The writer, therefore, came to suspect that the younger Cary moraines buried beneath the Valders till sheet might be Port Huron equivalents. By the thesis of this paper, the Glenwood static level was destroyed and the lake lowered by reason of Maumee-Arkona-Whittlesey discharge into Lake Chicago. Because there were but two episodes of large contribution from the east, and but two lowering episodes in Lake Chicago's history, it is reasoned that this Maumee-Arkona-Whittlesey discharge occurred before the Bowmanville-Lake Wayne episodes and therefore before the Port Huron moraine was built. The Port Huron moraine should coincide approximately with the first-attained Calumet level (fig. 2.). Suspicion therefore rose regarding the existence, as reported by Goldthwait (1908) Leverett (1915) and Alden (1918) of "faintly developed" Glenwood shore lines on the red drift of Wisconsin and the Port Huron moraine in Michigan. It seemed plausible to consider that the Valders drift, younger than Port Huron, was deposited late in Calumet time, perhaps too late to receive good Calumet shores. But all these suppositions involved challenges of earlier interpretations, and field study in Wisconsin and Michigan became imperative if the Lake Chicago thesis was to stand.

FIELD EXAMINATIONS, REINTERPRETATIONS AND RECORRELATIONS

The revision and elaboration of the geology of the Chicago region, a project of the Illinois State Geological Survey, thus came to include a restudy of considerable territory farther north. In it, some surprising conclusions were reached. Because they depart markedly from those of earlier students, some detail must be given to setting them forth.

SHORE LINES IN WISCONSIN

Alden (1906) found in mapping for the Milwaukee folio that the sheet of red drift reached southward no farther along

the Lake Michigan coast than the northern part of that city and that its overlap there on earlier drift nowhere reached more than a mile and a half back from the lake shore. Beneath it and resting on the blue Lake Border till, he found a stratified gravel, sand and clay which he interpreted as a Glenwood deposit made in front of an advancing Lake Michigan glacial lobe that finally buried it beneath the red till. He found no Lake Chicago shore lines within the quadrangle for the coastal land is everywhere too high above present cliffs. Numerous well logs showed the top of the water-laid member to be as much as 70 to 80 feet above Lake Michigan and this he ascribed to deposition in marginal ice-dammed lakes and streams of Glenwood time.

Alden interpreted a sand and gravel deposit in the valley of Milwaukee River, lying just west of the red till, as outwash contemporaneous with the red till but made no suggestion regarding its relation to Lake Chicago. The many new exposures since Alden's study amply support his interpretation that Milwaukee River valley, earlier mouthing farther north, became blocked by the red till and the closed depression thus formed was aggraded full, the glacial stream then taking a new course southward to the present mouth, crossing a tract of dense, hard, older till on which no deposit was made. Hence this Milwaukee valley train did not terminate in a Lake Chicago delta whose altitude would date the red drift episode.

Goldthwait (1907) found definite Glenwood and Calumet shore lines as far north as Racine but none thence northward to Port Washington. Six miles north of this city he found "a vague sloping platform, hardly sandy or gravelly in composition, with a doubtful bluff behind it" which he said Alden had suggested[7] might be a Calumet shore line. Two miles farther north (sec. 7, T 12 N, R 23 E) this feature is "more definite and takes the form of two low bars of gravel, the higher a short but well-formed gravel ridge . . . 60 feet above the lake and the lower a very flat bar at 48 feet, hardly more than a flattening of the long, lakeward slope of the highest beach." Goldthwait admitted that correlation of these and other suggestive forms and deposits of that district "with the beaches of Lake Chicago south of Racine is a problem of

[7] Probably in text for the Port Washington folio, which was never published.

considerable difficulty" because of questionableness of origin and impossibility of securing definite markers for altitude measurements. Yet "the higher, less distinct beach ridges undoubtedly belong to Lake Chicago."

The writer, after examining most of this district, was far more doubtful than Goldthwait about the littoral origin of the so-called Glenwood features. The "short but well-formed gravel ridges" is composed of poorly sorted, very poorly stratified and but little worn cobble and pebble gravel with much sand and a few boulders. This material grades out laterally into sandy soil with pebbles, and that into the unmodified pink till. The hillock is a small kamey accumulation, its composition very unlike what a beach ridge would have. Its location in mid-width of the presumed wave-cut terrace proves that "vague, sloping platform" to be morainic, not littoral, in origin. Further evidence is the existence of a once closed morainic depression in this "terrace," now breached and drained by a ravine. The "very flat bar," however, is a gravelly beach ridge which Leland Horberg and the writer traced almost continuously for 2½ miles south of Goldthwait's locality.

Alden (1918) traced the red drift northward along Lake Michigan, finding that the belt along the coast widens to no more than 15 miles in the 75 miles from Milwaukee to Manitowoc. At this northern limit, however, the drift sheet is expanded westward to constitute two lobes, the western of which extends south down the Green Bay depression a few miles beyond Lake Winnebago. He found this red drift to override moraine ridges of the Lake Border system, the Kettle interlobate moraine and some Lake Border correlatives in the Lake Winnebago region. But he conceived of its own ridges as terminal and recessional red till moraines, nowhere suggesting the idea which Thwaites was later to stress; that these ridges are really older moraines entirely covered by a thin red till.

In this paper, Alden described, on the red drift between Port Washington and Manitowoc, "what appears to the writer to be the Glenwood shore line. . . . very faintly developed yet traceable. . . . along the west limit of a gently sloping flat plain or lake terrace, beyond which the surface of the drift rises more rapidly to the crest of the east ridge of the red clay series." He noted that "nowhere is there a definite beach", that "the flat terrace rises to a slight break in slope at the

Glenwood level with here and there slight traces of gravels, and west of this indefinite bank the surface becomes gently undulating", and finally that "though the phenomena in this lake border belt are scarcely definite enough to prove submergence in the waters of the Glenwood stage of Lake Chicago, they are just about what would be expected if such submergence lasted but for a comparatively short time. . . ."

Alden's conclusion was that the red drift was deposited during Glenwood time, that "north of this place (Milwaukee) there was an early Glenwood stage, then a stage of glaciation (without change in lake level) followed by a later Glenwood stage".

The writer would note that the "terrace" of Goldthwait's and Alden's quoted descriptions is far too wide and the "bluff" much too high to be the product of a short exposure to wave attack. The prism of excavated material would be greater than in any Glenwood cut shores at the south end of the lake. A "faintly developed" erosional shore would be a mere niching in the morainic slope. Furthermore, the "terrace" slopes considerably more than do wave-cut Glenwood terraces in till at the south end of the lake and it has at least one definite record of an unfilled morainic depression in it. Still further, a tracing across Sheboygan County encounters long stretches with comparable exposure toward the east where no perceptible break in slope could be recognized. And still further, the same kind of "break in slope" exists in several places well above any possibility of a Glenwood shore line, and even back between the morainic ridges.

Alden believed that a delta of Glenwood age overlay the red drift in southeastern Manitowoc County (1918, p. 330), about 100 miles north of that drift's southern limit. This Cleveland "delta" of Centerville Creek was examined in 1950 during a field conference on Pleistocene geology. A. C. Trowbridge, F. T. Thwaites, Leland Horberg and the writer agreed that: 1) The volume of the deposit is far in excess of what Centerville Creek could erode and transport in the time Alden allowed, a later Glenwood stage so brief that no definite shore lines were made, 2) The clean washed character of the "delta" sand and the lack of clayey layers in the 30-foot section record far more sorting than the creek could ever produce at this place, 3) The topographic setting indicates the deposit to be

outwash sand deposited in a low place in a morainic sag or trough when the Lake Michigan lobe of Valders age was still overlapping the local coast.

If the Glenwood shore, however faintly developed, is present on the Wisconsin red drift, that coast was surely exposed to the glacial lake during the entire Calumet stage. Alden found only "indications" of it and "a slight trace of a beach too poorly developed for certain correlation" between Racine and Sheboygan. He explained its absence as due to destruction by later wave work. Nevertheless, any remnants spared would be more than "slight traces" and "indications." Yet the only beach ridge which Horberg and the writer found was the "very flat bar", the base of whose lakeward slope was 40-45 feet above Lake Michigan. It can only be a weak Calumet shore line. The writer concludes that no record of the Glenwood level of Lake Chicago exists on the Valders red drift.

MORAINES IN WISCONSIN

A Pleistocene study by Thwaites (1943) covered portions of all of 13 counties lying west of Lake Winnebago, Green Bay and Menominee River, most of this area lying within the province of the Green Bay lobe. The western half is characterized by moraines of Cary age, the eastern half by the red drift which Thwaites named Valders. The most significant finding, from the present viewpoint, is that the southern portion of the easternmost Cary moraines are overridden by the Valders red till, yet traceable for some distance as ridged elevations in the thin Valders. Thwaites correlated his moraines with those named by Alden farther south in the Green Bay lobe, as Alden had earlier correlated his later Green Bay moraines of Cary age with units of the Lake Border system. All these correlations seem logical enough. If correct, Thwaites' Mountain moraine is the northern extension of Alden's St. Anna moraine (just south of Lake Winnebago). This, in turn, is the equivalent of the Lake Border system's easternmost ridge, a feature which reaches from the Illinois line to Random Lake, 12 miles north of Port Washington, where it disappears under the red drift. A gap of about 25 miles separates its northern visible end from the place where the St. Anna makes contact with the west side of the Kettle interlobate moraine.

Thwaites traced his easternmost and youngest Cary moraine, the Athelstane, southward and southeastward, under the Valders till cover, almost to Fox River. Its probable course thence should be northeastward, completing the loop all Green Bay moraines possess. This would bring it into the glacially unmapped territory north of Alden's and east of Thwaites' limits, there to enter the Interlobate complex and emerge on the east side as a correlative frontal ridge of the Lake Michigan lobe.

Thwaites showed on his generalized location map (fig. 1) a northward extension of the Kettle Interlobate moraine from Alden's area into southwestern and central Kewaunee County, where the coalescence of Lake Michigan and Green Bay moraines of this late Cary stage should occur. The Kewaunee County soil map depicts this interlobate area as a wedge-shaped tract, chiefly of Miami silt loam, tapering out to the north. Small irregular patches showing 8 different soil types, also peat beds and lakes, scattered throughout this area, are strongly suggestive of the Kettle moraine topography. Other soils of the county are distributed in dominantly north-south belts, the boundaries of those on the east inclining toward west of north, those on the west toward east of north, in a rough parallelism with the sides of the interlobate wedge. The county's drainage pattern largely conforms also to this northward convergence of soil belts, showing morainal sag control. When the glacial map of this district, now being made by Thwaites and Bertrand, is published it should differ only in details from this very expressive soil map.

There are at least seven morainal ridges in the red drift sheet which are cut in diagonal section by the Lake Michigan cliffs. Only one, just north of Port Washington, has been examined during the present study. It has little more than 12-15 feet of red till overlying a brown till in its cliff sections. In the sag between it and the next ridge to the west, the red till is at least 20 feet thick, its surface lying 30 feet or so lower than its base in the ridge. This is good evidence of veneering. Excavations near the power station in Port Washington show the red till to overlie older drift at various altitudes, suggesting that a Sauk Creek valley existed here before the red till was deposited.

It is therefore forecast that these red drift ridges along the Lake Michigan coast will all prove to be buried Cary mor-

aines and that both Lake Border and, farther north, Port Huron units will be identified. The absence of Glenwood records on the red drift and the existence of only a weak Calumet record indicates that this readvance of the Lake Michigan lobe came late in Calumet time, just before the high waters of Lake Warren discharge started the lowering from Calumet to Toleston levels.

Near Two Creeks, a "forest bed" and peat deposit at the base of the red till is exposed in the sea cliffs a little above the lake surface. Stumps shallowly rooted in the peat project a few inches up into this till, showing that the wood was green, tough and elastic at the time of overriding. Branches several feet long were worked over and came to rest, battered but intact, as much as 5 or 6 feet up in the red till. This deposit, therefore, is no earlier vegetal accumulation, fortuitously uncovered but spared from destruction, and then reburied. Thwaites (1937, p. 83) is justified in his picture of "knocking down of live trees by advancing ice which deposited red till." If the red till be of Glenwood age, this forest bed must be either: 1) pre-Glenwood, or 2) the record of an otherwise unknown law-water stage *interrupting* the Glenwood high-water stage. The first conclusion is obviously impossible. Only by the second could there be Glenwood shores on the red till sheet!

The writer, convinced that no such shores exist, would correlate the Two Creeks forest bed with the peat, wood fragments and shells of the Evanston district, Illinois, first reported in Dr. Edmund Andrews' classic paper (1870) and elaborately described by Baker (1920). Baker proved that the chief deposits are *in situ*, not drifted to position as Alden, Goldthwait and Leverett had suggested, and that they are post-Glenwood, pre-Calumet in age. Their low altitude (590) establishes the verity of the low-water stage which Baker named Bowmanville.

SHORE LINES IN MICHIGAN

Goldthwait (1908) reported the existence, with altitudes, of abandoned lake shores above the Algonquin strand along the east side of Lake Michigan as far north as Ludington. He remarked on the paucity and the fragmentary and "obscure" character of these shore lines from Grand River north.

Leverett's first published map of glacial features of the southern peninsula is dated 1911. It accompanied a publication dated 1917. The next map, appearing in 1915 in Monograph 53 was by Leverett and Taylor. A third map, by Leverett, with cooperation of Taylor and others, is dated 1924 and has no accompanying text. Chapter 14 of the monograph, written by Leverett, deals with Glacial Lake Chicago's shores, chiefly in Michigan.

Changes of the glacial lake shore lines in this series of maps are most marked along the Lake Michigan coast north of Grand River. Leverett's text in the monograph indicates doubt as to the location, even the existence, of the highest shore in some places where altitude and exposure would seem to promise its formation. His statement in 1917 (p. 123) was that "the highest beach is so weak as to be traced with some difficulty on the slopes of the outer ridges of the (Port Huron morainic) system from near Muskegon northward." He reported a definite Calumet shore line, saying in the monograph that it "appears throughout its course as a single ridge and a strong one." Neither he nor Goldthwait found any pre-Algonquin shore lines north of Manistee.

By the thesis of this study, Lake Chicago was lowered from its Glenwood level during the first of two episodes of large contributions from eastern lakes. The Port Huron moraine, built at the close of this first episode, therefore could not possess Glenwood shore lines along the Lake Michigan coast. Prompted by the incompatibility of the Goldthwait and Leverett statements with the attractive theory, the writer made about a thousand mile traverse in the coastal belt between Grand River and Grand Traverse Bay, following Leverett's earlier and later mapping of the Glenwood shore line. No shore was found! Questioning his own ability to recognized faint shore lines, the writer repeated most of these traverses in company with Stanard Bergquist, Leland Horberg and Morris Leighton. Without specifying details of the earlier misinterpretations and subjective recognitions, it will be sufficient here to record that all three men agreed they could identify no Glenwood shore lines in Michigan north of Muskegon.

Another feature of the Michigan shore line problem is a deltaic deposit made by Glacial Grand River in Lake Chicago. Leverett showed it on all three of his glacial maps and briefly

described it in 1915 (p. 352) as having a top level at Glenwood altitudes, trenched about 25 feet deep in places by Grand River outlet as Lake Chicago fell to the Calumet level. The outlet's last functioning was for the Lake Warren discharge. Because Leverett recognized no Toleston trenching, by implication he considered both episodes of westward discharge down Grand River to have occurred before the second lowering of Lake Chicago.

Two days of field study with the aid of the Ottawa County soil map (1922) and the Holland and Muskegon topographic maps (1928-1930) showed that this Allendale delta covers more than three times the area Leverett estimated and has two well-developed Toleston portions, one along the lower course of Grand River, the other along the Zeeland distributary. Because the Lake Chicago bottom here had a very gentle slope, most of the delta is thin, the Calumet additions lying west of the Calumet distributary channels and the Toleston portions disappearing under the great dune belt along the present Lake Michigan shore.

The two trenchings, with their deposits at Lake Chicago's second and third levels and with correlative terraces upstream along Grand River valley at least as far as Ada indicate clearly that Glacial Grand River continued to function until the Toleston level had been attained. Lake Warren's discharge, therefore, continued until that same time and the Allendale delta fits perfectly into the chronology and correlation scheme herewith presented.

MORAINES IN MICHIGAN

A strongly expressed moraine lies along the Lake Michigan shore from Manistee north, and has a lobate form around the south end of Grand Traverse Bay. This, the Manistee moraine, is of clay till about as red as the typical Valders in Wisconsin. Leverett believed that, in its further course southward, the Manistee moraine went under the surface of the lake, there curved westward and northward and reappeared in Wisconsin as the Two Rivers moraine of Alden.

The next older moraine in Michigan is the second ridge of the Port Huron system which, although containing reddish till in places (as do most till sheets), prevailingly is not at all red or pink. This system was mapped and described as

reaching the Lake Michigan shore from the northeast near Ludington and as continuing southward along the coast to include the small Whitehall moraine, about 10 miles north of Muskegon. Here it disappeared under the lake. A field conference between Alden and Leverett in 1910 led to their conviction that this Port Huron system emerged at Milwaukee as the red drift sheet. Confident of the existence of both Glenwood and Calumet shore lines on this drift, Leverett wrote (1915, p. 310) as follows: "The moraine leading north from Two Rivers has no beach higher than the third beach (Toleston) of Lake Chicago, which is there about 25 feet above Lake Michigan. But within a few miles south of Two Rivers, on the plain between the lake and one of the earlier red drift moraines, beaches and river deltas are developed up to about 60 feet above Lake Michigan. There could scarcely be better grounds for correlation than are presented in the relation of these moraines to the beaches of Lake Chicago." The writer believes, however, that there are better grounds for a better correlation.

The red drift limits, as mapped in Wisconsin and Michigan, early seemed to the writer to offer a neglected possibility of correlation, especially in view of the admitted weakness of the supposed Glenwood shores on which these students were making their correlation. Furthermore, if the Port Huron moraine did have Glenwood shores on its slopes, the Maumee-Arkona-Whittlesey discharge to Lake Chicago had not sufficed to bring about a lowering to the Calumet stage and some cause, not yet envisaged by anyone, must be found to explain those two lowerings and the two associated static levels.

In the above-noted traverses between Grand River and Grand Traverse Bay, a surprising discovery was that the red till of Michigan extends along a coastal belt for 65 miles south of Manistee. The southernmost units of Leverett's Port Huron moraine, near Whitehall, are of red or pink till or are heavily veneered with it. Lake bluffs, ravine slopes, basement excavations, road cuts, even freshly plowed fields showed this color. No till of any other hue was seen except below the red. The belt of country thus characterized extends in places 10 miles back from the lake. In some morainic tracts, the eastern part is lacking in the red till but topographically

differs little from the western part where overlaid by this younger glacial deposit. When posted on a map, the pattern indicates that the Manistee moraine-building ice, reaching far south of the limits assigned by Leverett, crowded eastward out of the lake basin to overlap the Port Huron moraine and to reach about 20 miles farther south. The outer part of that older moraine system appears to go under the lake in southern Oceana County. In these observations and interpretations, Bergquist, Horberg and Leighton concur with the writer.[8]

The Whitehall moraine therefore is interpreted as a part of the Manistee moraine, built by a readvance of the Lake Michigan lobe after an extensive retreat from the Port Huron pause and a realignment of flow lines from Canadian glacial sources sufficient to make this contrast in color of the till. Obviously, this pattern is almost identical with that of the red till in Wisconsin and a correlation is called for. It will be open to criticism, however, unless some Port Huron equivalent in Wisconsin, other than that proposed by Alden and Leverett, exists.

The revision, therefore, considers that morainic ridges emerging from the lake in Kewaunee and southern Door counties are buried Port Huron correlatives and are equivalent to the St. Anna and Athelstane moraines of the Green Bay lobe. Thus the red Manistee and Whitehall moraines are earliest Mankato drift in Michigan as the red Valders drift is in Wisconsin, and thus the Port Huron moraine becomes latest Cary.

If the Manistee and Whitehall moraines are correlative, meltwater must have flowed southward, subparallel to a continuous ice front, for 100 miles or so before it could enter Lake Chicago. Reconnaissance shows that spillways for such water, with properly related altitudes and gradients, exist among the unit members of the Port Huron system. Although undoubtedly used earlier by Port Huron meltwater rivers, the channelling that has occurred along the westernmost of these and the limitation of pitted plain character to their highest terraces seem good evidence of post-Port Huron use.

It also appears that, as the ice front shrank from the

[8] A reddish till exposed in the bluffs of Muskegon River valley at Newago, 32 miles directly east of Whitehall, lies beneath the Lake Border moraines and is not to be correlated with the pink to red drift of the Manistee-Whitehall moraine. Leighton has suggested in conversation that it may be correlative with the pink Bloomington till of Illinois.

Manistee-Whitehall moraine, the withdrawal began at the south, near Muskegon, and that more northerly and shorter routes for meltwater seeking the lake were successively opened; at White River, at Pentwater River, at Pere Marquette River and finally at Manistee River.

At the maximum of the Manistee-Whitehall advance, a lake was formed in the lower Manistee River valley by the ice dam at the valley mouth. Its pink laminated clays (at High Bridge, 15 miles east of Manistee) became buried under a valley train leading west to Lake Chicago when glacial withdrawal from the moraine occurred in this latitude but while meltwater was still being discharged across more northern portions of the moraine. The concept here advanced is that the Lake Michigan lobe, much elongated in latitude, shrank from its margining moraines in the fashion that a valley glacier, elongated in altitude, withdraws from its laterals. Detailed field study must wait until the region has been topographically mapped but the laminated clays seem impossible to explain by Leverett's and Alden's correlations.

SUMMARY

The writer believes that good evidence and reasoning support the following conclusions:

1. The Tinley moraine and valley train alone constituted the dam for Lake Chicago.
2. Only variations in discharge could have caused variations in the rate of the Tinley dam's erosion to produce Lake Chicago's successive high-water stages.
3. Only the influx of Maumee-Arkona-Whittlesey water can explain the lowering from Glenwood to Calumet levels.
4. Only the combined Bowmanville and Lake Wayne diversions can be correlated with the cessation of Lake Chicago's discharge at the first-attained Calumet level.
5. Forward sweeping of shore drift as Lake Chicago rose again from the Bowmanville low-water level produced the strong Calumet beach in the relatively short time the dam allowed.
6. Lake Warren's discharge, poured into Lake Chicago, caused outlet deepening and the lowering from Calumet to Toleston levels.
7. Beginning of Mankato time, marked by deposition of the red Valders and Manistee (revised) drift, occurred during the Calumet stage of Lake Chicago.
8. The Port Huron moraine is of late Cary age, not correlative with the Valders red drift.

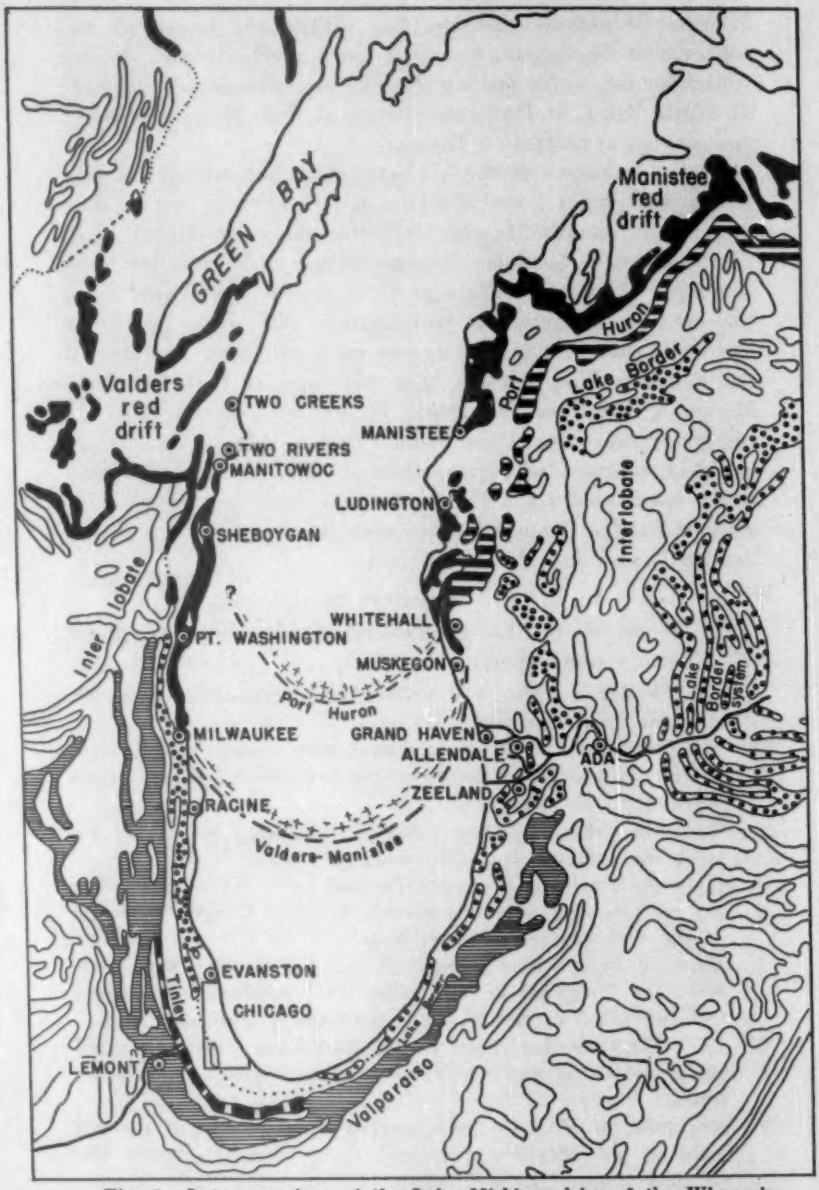

Fig. 1. Later moraines of the Lake Michigan lobe of the Wisconsin ice sheet. Modified from Glacial Map of North America, Geol. Soc. America 1945.

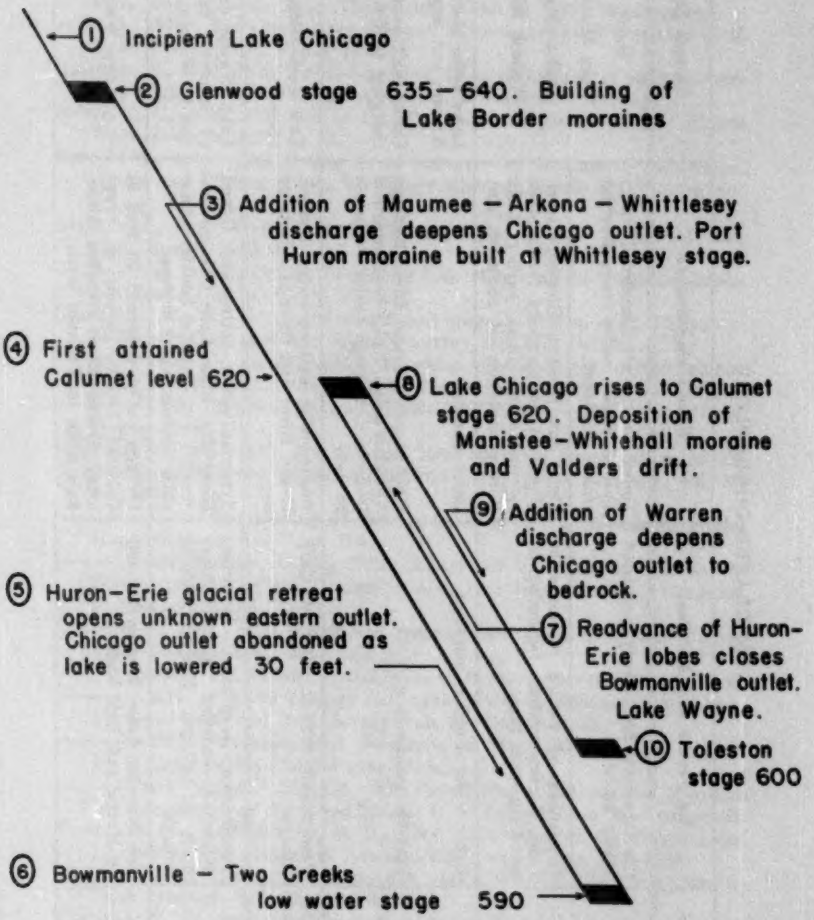
① Incipient Lake Chicago
② Glenwood stage 635–640. Building of Lake Border moraines
③ Addition of Maumee – Arkona – Whittlesey discharge deepens Chicago outlet. Port Huron moraine built at Whittlesey stage.
④ First attained Calumet level 620
⑤ Huron–Erie glacial retreat opens unknown eastern outlet. Chicago outlet abandoned as lake is lowered 30 feet.
⑥ Bowmanville – Two Creeks low water stage 590
⑦ Readvance of Huron–Erie lobes closes Bowmanville outlet. Lake Wayne.
⑧ Lake Chicago rises to Calumet stage 620. Deposition of Manistee–Whitehall moraine and Valders drift.
⑨ Addition of Warren discharge deepens Chicago outlet to bedrock.
⑩ Toleston stage 600

Fig. 2. Stages of Lake Chicago correlated with contemporaneous moraines and eastern lakes.

TABULATED CHRONOLOGY

Lake Chicago Events	*Ice Fronts and Moraines*	*Functioning Outlets*	*Eastern Lakes*
"Incipient" Lake Chicago.	Glacial retreat from newly completed Tinley moraine.	Tinley moraine crest eroded down to level of Tinley valley train. Boulder armor developed.	Early Lake Maumee, discharging to Wabash River.
Glenwood level.	Deposition of earlier moraines of Lake Border system, beginning in mid-Glenwood time.	Tinley dam holds up Glenwood level. Higest Allendale delta levels made by meltwater from earlier Lake Border moraines of Saginaw lobe.	
Lowering to first-attained Calumet level.	Later Lake Border moraines. Port Huron moraine.	Imlay channel. Ubly channel. Grand River trenches Allendale delta. Tinley boulder armor ineffective, Chicago outlet deepened 20 feet.	Later Lake Maumee. Lake Arkona and Saginaw, and Lake Whittlesey, all discharging to Grand River.
Bowmanville low-water stage and Two Creeks forest bed.	Pronounced retreat. End of Cary subage.	Bowmanville eastern outlet opened. Grand River and Chicago outlets go dry.	Low stage without known record.
Rise back to Calumet level.	Pronounced readvance, Manistee-Whitehall moraine and Valders drift at climax. Early Mankato subage.	Syracuse outlet active and Grand River dry, while Lake Chicago discharges over Calumet boulder armor until Warren water arrives.	Lake Wayne during part of interval, followed by rise to Warren level.
Lowering from Calumet to Toleston level.	Ice dam for Lake Warren far out in Huron and Erie basins.	Chicago outlet deepened 20 feet as Calumet boulder armor is swept away. Grand River trenches Allendale delta to Toleston level.	Lake Warren.

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NEOHIPPARION LEPTODE (MERRIAM) FROM THE PLIOCENE OF NORTHWESTERN NEVADA

CHESTER STOCK*

ABSTRACT. A complete skull and skeleton of a fossil horse, *Neohipparion leptode*, are described from the Hemphillian stage, middle Pliocene (Thousand Creek Beds, northwestern Nevada). Prior to the discovery of this specimen a smaller individual of *Neohipparion whitneyi* Gidley was known from the Clarendonian stage, lower Pliocene (Little White River, near the Rosebud Indian Agency, South Dakota). Skeletal ratios indicate that *Neohipparion* is characterized by greater elongation of the distal limb segments (radius, metacarpus, tibia, metatarsus) in relation to the proximal segments (humerus, femur) than *Equus*. In this regard, *Neohipparion leptode* differs less from *E. caballus* than does *E. whitneyi*.

INTRODUCTION

ONLY one example of a complete skull and skeleton of *Neohipparion*, other than that described in the present article, has been available. Prior to the discovery of the specimen of *Neohipparion leptode* from the Hemphillian stage, middle Pliocene (Thousand Creek Beds, northwestern Nevada), the complete skeleton of an individual representing this genus in the history of the horse group was the type of *N. whitneyi*. This smaller individual came from Little White River, near the Rosebud Indian Agency, South Dakota, and was described in 1903 by Gidley (1903). It is from the Clarendonian stage, lower Pliocene.

It seems especially desirable to place on record the present material, not only because of its unusual state of preservation, but likewise in order to have the information available for reference in studies now underway on species of *Neohipparion* from the Pliocene of Mexico.

Preparation and mounting of the skeleton of *N. leptode* are the work of William Otto, member of the technical staff, Division of the Geological Sciences, California Institute of Technology.

* The untimely death of Dr. Chester Stock on December 7, 1950, at the height of his scientific career, comes as a heavy blow to all those associated with him. As a step in carrying forward the vertebrate program at California Institute so vigorously prosecuted by Dr. Stock, an effort is being made to see through the press those remaining works left in essentially complete form. C. W. MERRIAM

COMPARISON OF MATERIAL

Skull.—The skull, No. 54 C.I.T. Coll., belongs to an adult individual. The specimen displays some damage due to crushing, and a few parts have been restored. The latter are seen in the illustrations (plates 3, 4). Apparently the upper surface of the skull was subjected to pressure, for the frontals are badly cracked and the cranium has been flattened somewhat. The upper half of the face has suffered a horizontal cracking on the left side, and the crack has given definition to the lower margin of an oval-shaped area over which the outer surface of the maxillary is broken inward and is incompletely preserved. On the right side the disappearance of the facial wall of the maxillary over the oval-shaped area exposes what appears to be the surface of one of the turbinate bones. The oval-shaped area lies in front of the deep pit of the malar fossa. There is no pre-orbital depression other than the pit in the malar bone.

The skull of *Neohipparion leptode* is larger than that of *Neohipparion whitneyi*, the linear difference being approximately 15%. However, the size of the skull in relation to the size of the skeleton is smaller in *N. leptode* than in *N. whitneyi*. In size, *Neohipparion leptode* resembles *Hipparion richthofeni* and *Hipparion fossatum* from the Pliocene of China (Sefve, 1927), and is smaller than *Hipparion dermatorhinum*. The type of *Proboscidapparion sinense* is distinctly larger. A comparison of cranial indices of the Nevadan and Chinese skulls shows that in the former the cephalic and faciocephalic indices are greater. Only in the instance of *Hipparion fossatum*, among the Chinese skulls, is the cranio-cephalic index a trifle larger than in No. 54.

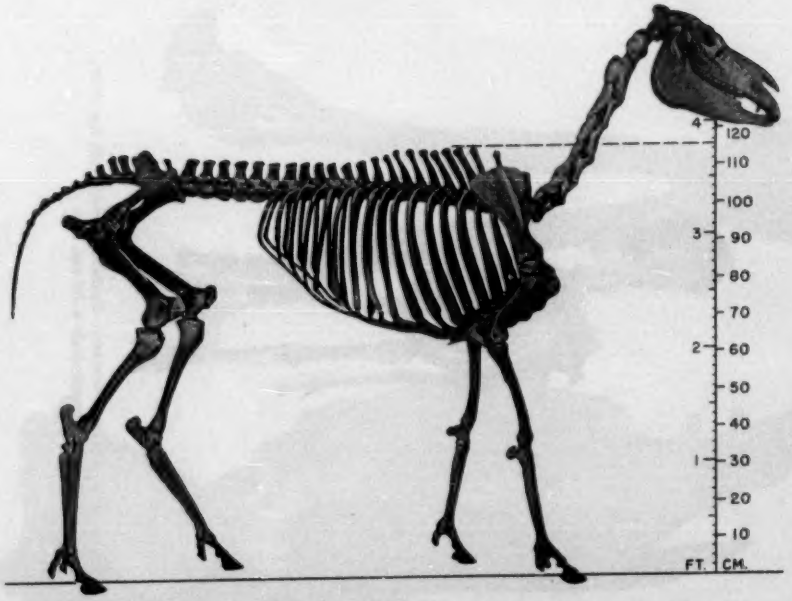
While *Neohipparion leptode* has a more robust skull than *Neohipparion whitneyi*, the height of the former, as measured from the alveolar border of M1 to the upper profile, has the same relation to the distance from the outer border of the orbit to the front incisors, as in *Neohipparion whitneyi*. The cheek-tooth series, in relation to total length of skull, occupies less space in *Neohipparion leptode* than in *Neohipparion whitneyi*. The orbit is situated farther back than in the latter, for its anterior border is in vertical line with the posterior end of M3 or slightly in back of this tooth. Below the malar fossa the crista facialis extends forward to the extent shown in the

skull fragment previously described (Merriam and Stock, 1928). At the front end of the cheek-tooth series the lateral wall of the maxillary is deeply indented. The muzzle is blunt and wide, but there is no great lateral flaring of the terminal portion of the snout relative to the constricted region between canines and cheek-tooth series. The anterior border of the postnarial notch has a position like that in *Neohipparion whitneyi*.

The maxillary foramen or posterior opening of the infraorbital canal is slit-like and has an oblique position. This foramen and the sphenopalatine foramen are situated in a recess which is not so deep as in *Equus*. Below the sphenopalatine foramen is the posterior palatine opening which faces directly backward and can, therefore, be more readily discerned from the rear than in *Equus*. The anterior palatine foramina are close to the postnarial border and are situated opposite the posterior portion of M2.

Measurements (in millimeters) of Skull and Mandible of *Neohipparion leptode*, No. 54 C.I.T. Coll.

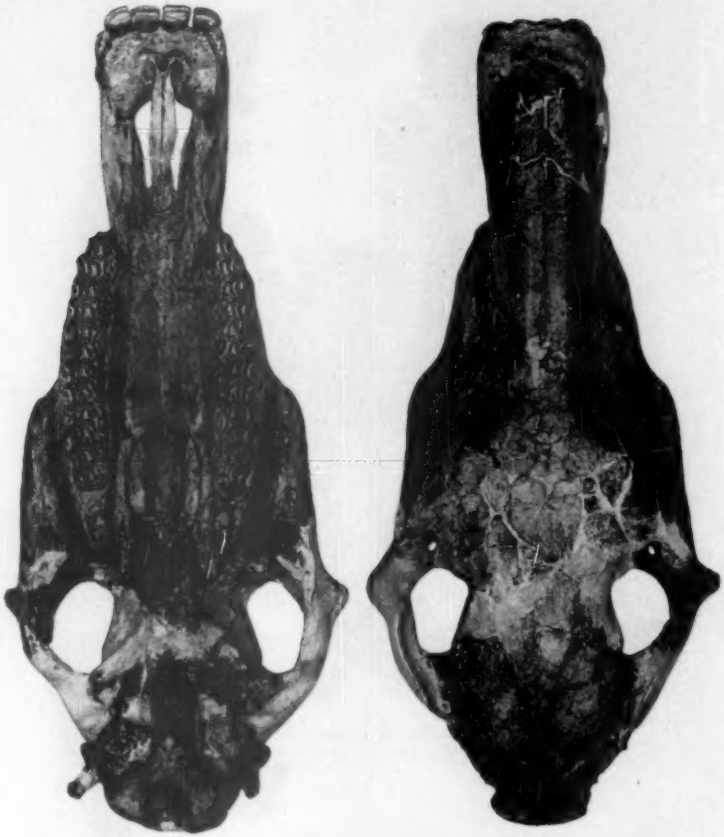
Length from anterior end of premaxillaries to occipital crest	451.0
Length from anterior end of premaxillaries to posterior face of occipital condyles	432.0
Basilar length	402.0
Length from anterior end of nasals to occipital crest	415.0
Length of face from anterior end of premaxillaries to middle of line connecting posterior borders of orbits	323.0
Length of cranium from middle of line connecting posterior borders of orbits to occipital crest	143.1
Length from anterior end of skull to posterior end of palate on middle line	226.0
Anteroposterior diameter of orbit	58.7
Dorsoventral diameter of orbit	42.8
Length from anterior margin of incisors to level of posterior margins of upper third molars	260.0
Length from anterior border of canine to posterior end of M3	208.6
Transverse diameter of muzzle	71.9
Length of nasal-maxillary notch	72.3
Width of nasals at end of nasal-maxillary notch	46.3
Least width between orbits	126.3
Frontal width at posterior borders of orbits	194.3
Width of postorbital constriction of brain-case	*ap.* 74.6
Width of brain-case	92.2
Mastoid width	104.2
Width between outer sides of paroccipital processes	99.2
Width across occipital condyles	72.5
Greatest width of posterior nares	37.5
Width of palate between inner walls of first molars	59.0
Width across outer sides of upper third incisors	70.0



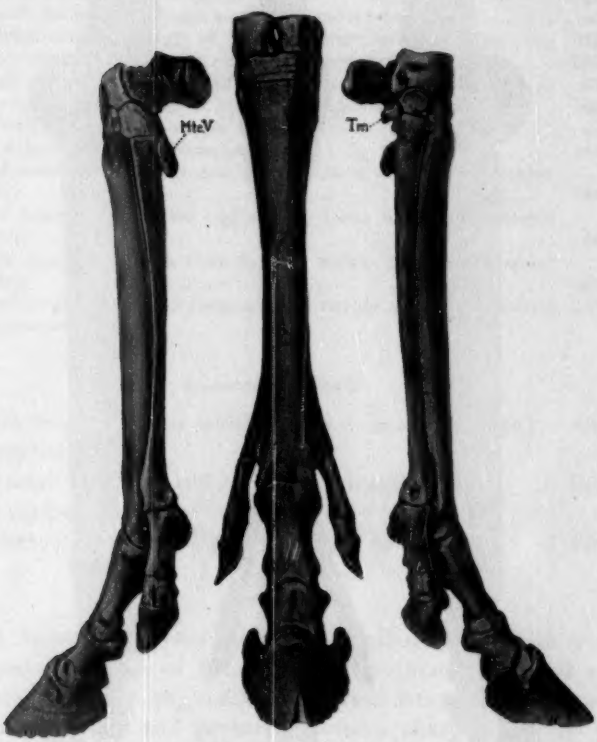
Neohipparion leptode (Merriam). Skeleton viewed from the right side.

Neohipparion leptode (Merriam). Skeleton viewed from the front; approximately x .06 nat. size.

Neohipparion leptode (Merriam). Skull as viewed from left side; lower jaw in superior view; x .25 nat. size.



Neohipparion leptode (Merriam). Skull, superior and inferior views; x .25 nat. size.



Neohipparion leptode (Merriam). Right front foot, medial, anterior and lateral views; Mtc.V, vestigial metacarpal V; Tm, trapezium; x .25 nat. size.

Neohipparion leptode (Merriam). Right hind foot in medial, anterior and lateral views; x .25 nat. size.

Length of cheek-tooth series, $\underline{P2}$-$\underline{M3}$	140.9
Length of diastema between C and $\underline{P2}$	56.1
Length of diastema between $\underline{I3}$ and C	25.1
Least width between diastema borders posterior to canines	44.1
Length from anterior margin of I1 to posterior margin of jaw	363.0
Length anterior margin of I1 to posterior border of $\underline{M3}$	257.8
Length of diastema between canine and $\underline{P2}$	67.7
Width across outer borders of lower third incisors	69.4
Least width of mandible across diastema	40.7
Length of lower cheek-tooth series, $\underline{P2}$-$\underline{M3}$	147.1
Depth of ramus at anterior end of $\underline{P2}$, taken normal to alveolar border	51.8
Depth of ramus at posterior end of $\underline{M3}$, taken normal to inferior border	88.1
Height of ascending ramus from inferior border to tip of coronoid process	221.5
Height of ascending ramus from inferior border to top of condyle	189.5

ap., approximate.

Indices of Skull

Cephalic index (frontal width x 100 ÷ basilar length)	48.3
Facio-cephalic index (facial length x 100 ÷ basilar length)	80.3
Cranio-cephalic index (cranial length x 100 ÷ basilar length)	35.6

Dentition

Both upper and lower incisors are robust teeth with well-developed infoldings of the enamel. The upper and lower canines are likewise strong teeth with crowns laterally compressed and with anterior and posterior borders sharply defined. As in specimen No. 27126 U.C.C. of *Neohipparion leptode* (Merriam and Stock, 1928) from the Thousand Creek Pliocene, $\underline{P1}$ is absent. The cheek-teeth are similar to those in the latter, but are more worn. The fossette borders show a moderately complex pattern of plications. The overall enamel pattern of their teeth is remarkably constant; such differences as prevail are due in large measure to stage of wear of the tooth crown.

The protocone is a large, elongate and compressed cusp, pointed at each end. Both upper and lower cheek-teeth are well-cemented. The latter resemble those in No. 27126. In teeth behind $\underline{P2}$ the grove between metaconid and metastylid is deep and wide, and the floor of this groove shows no fold in the enamel. Again, in these teeth, a spur of enamel projecting backward from the inner base of the paralophid is prominent

in the premolars (with the exception of P$\underline{2}$), and less so in the molars. The pli caballinid and parastylid are present but are not so prominent as in No. 27126. The entoconid is outlined

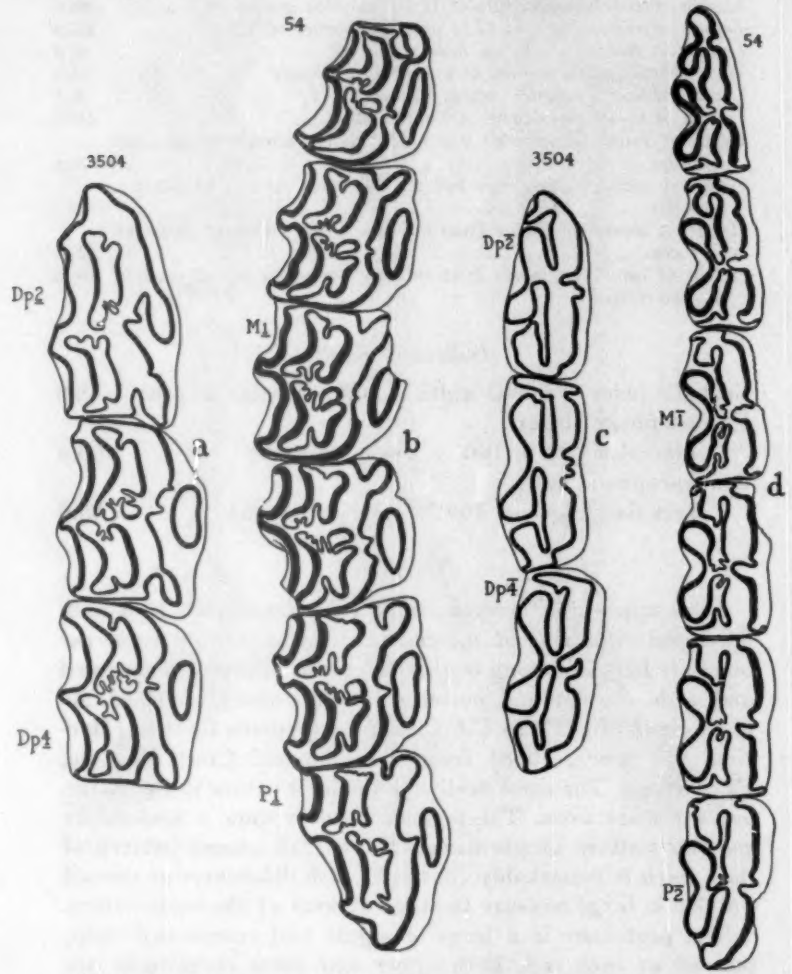


Figure 1. *Neohipparion leptode* (Merriam). Upper and lower cheek-tooth series, occlusal views. *a*, Dp$\underline{2}$, $\underline{3}$, $\underline{4}$, No. 3504; *b*, P$\underline{2}$-M$\underline{3}$, No. 54; *c*, Dp$\overline{2}$, $\overline{3}$, $\overline{4}$, No. 3504; *d*, P$\overline{2}$-M$\overline{3}$, No. 54.

All figures nat. size.
Calif. Inst. Tech. Vert. Paleont. Coll.
Thousand Creek Pliocene, northwestern Nevada.

by an enamel border which forms a pointed projection at the outer anterior base of the cusp.

Measurements (in millimeters) of Dentition of *Neohipparion leptode*

	No. 54 C.I.T.	No. 27126 U.C.C.*
I1, greatest transverse diameter	15.2	15.4
I2, greatest transverse diameter	16.2	16.6
I3, greatest transverse diameter	...	...
C , greatest anteroposterior diameter	10.0	4.7
P2, anteroposterior diameter	28.5	27.1
P2, greatest transverse diameter	21.4	20.7
P3, anteroposterior diameter	23.6	24.2
P3, greatest transverse diameter	22.6	23.1
P4, anteroposterior diameter	23.2	22.8
P4, greatest transverse diameter	22.9	22.5
M1, anteroposterior diameter	23.0	23.0
M1, greatest transverse diameter	22.0	22.6
M2, anteroposterior diameter	22.1	22.3
M2, greatest transverse diameter	20.6	21.0
M3, anteroposterior diameter	21.7	22.7
M3, transverse diameter	16.7	17.3
Length of upper cheek-tooth series, P2-M3	140.6	141.0
I1, transverse diameter	14.4	14.3
I2, transverse diameter	14.9	...
I3, greatest diameter	13.8	12.1
C , anteroposterior diameter	9.4	4.1
P2, anteroposterior diameter	25.9	24.8
P2, greatest transverse diameter	13.2	13.0
P3, anteroposterior diameter	24.3	23.8
P3, greatest transverse diameter	13.3	14.5
P4, anteroposterior diameter	22.8	23.7
P4, greatest transverse diameter	12.9	14.4
M1, anteroposterior diameter	23.9	22.8
M1, greatest transverse diameter	12.0	13.0
M2, anteroposterior diameter	23.1	24.2
M2, greatest transverse diameter	11.3	12.6
M3, anteroposterior diameter	25.6	25.0
M3, greatest transverse diameter	10.8	10.4
Length of lower cheek-tooth series, P2-M3	146.0	144.3

* Univ. Calif. Vert. Paleont.

Measurements (in millimeters) of Skeleton of *Neohipparion leptode* No. 54 Calif. Inst. Tech. Vert. Paleont. Coll.

Height to tip of spine of 3rd dorsal	1156
Axial skeleton, skull, condylobasal length	432
Axial skeleton, skull, frontal width	194
Axial skeleton, vertebral column, 31 presacral vertebrae	1533
Axial skeleton, vertebral column, 7 cervicals, total*	531
Axial skeleton, vertebral column, 18 dorsals, total	722

Axial skeleton, vertebral column, 6 lumbars, total	280
Axial skeleton, vertebral column, 5 sacrals, total	183
Axial skeleton, vertebral column, 17 caudals, total	499
Appendicular skeleton, fore limb, total length*	1101
Appendicular skeleton, scapula, total length	278
Appendicular skeleton, humerus, total length	256
Appendicular skeleton, radius, total length	296
Appendicular skeleton, metacarpal III, total length	251
Appendicular skeleton, hind limb, total length*	1061
Appendicular skeleton, femur, total length	347
Appendicular skeleton, tibia, total length	352
Appendicular skeleton, metatarsal III, total length	279

* According to method of measurement used by Gidley (1903).

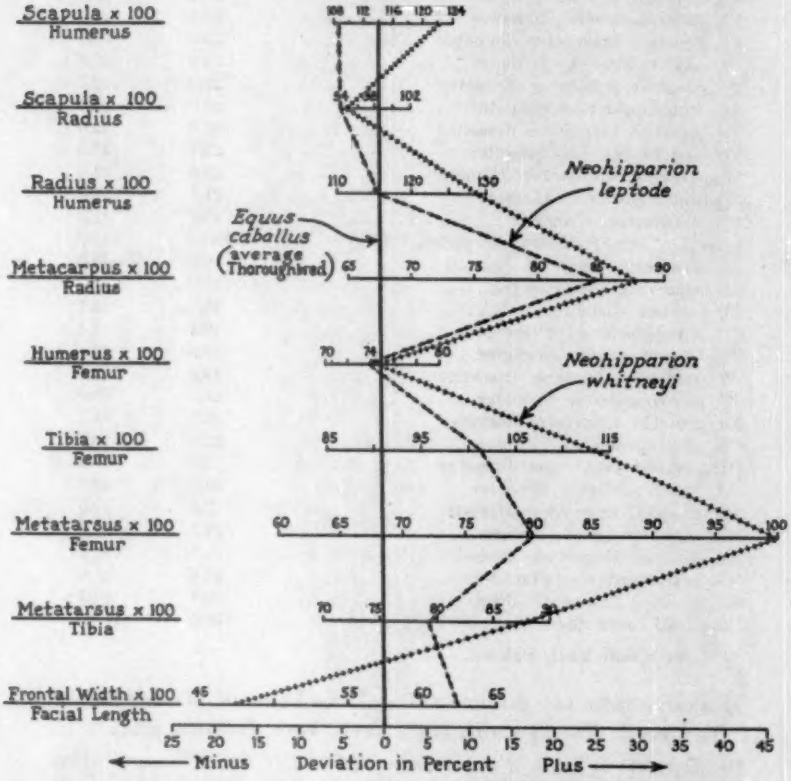

Scapula x 100 / Humerus
Scapula x 100 / Radius
Radius x 100 / Humerus
Metacarpus x 100 / Radius
Humerus x 100 / Femur
Tibia x 100 / Femur
Metatarsus x 100 / Femur
Metatarsus x 100 / Tibia
Frontal Width x 100 / Facial Length
Neohipparion leptode
Equus caballus (average Thoroughbred)
Neohipparion whitneyi
25 20 15 10 5 0 5 10 15 20 25 30 35 40 45
Minus Deviation in Percent Plus

Figure 2. Diagram showing relative proportions of skeletal elements in *Equus* (average modern Thoroughbred) and *Neohipparion*.

Feet.—The front foot is practically complete. Unfortunately, since the illustration was made (plate 5), the trapezium was lost. On the opposite side, articulating with the upper end of metacarpal IV is the vestigial metacarpal V. The latter element is 23.2 mm. long by 11.7 mm. wide. At the upper end the articulating facet has an oblique trend.

Metatarsals II and IV are complete and each carries the full complement of phalanges. The tip of phalanx III in these digits reaches a level slightly below the articulation of phalanges I and II of the third digit.

Thus while the downward extent of the lateral toes is about like that in *Merychippus isonesus*, as shown by Osborn (Osborn, 1918, plate 41), their total length in relation to length of lateral metacarpals is greater in *Neohipparion* than in Merychippus.

The terminal phalanx of digit III is wider in relation to its length as measured along the upper profile in *Neohipparion* than in *Merychippus*.

In the hind foot (see plate 6) the lateral metatarsals are more slender than in *Merychippus* (Osborn, 1918, plate 2). As in the front foot, the terminal phalanx of digit III is broader in relation to the length of this phalanx as measured along its upper profile than in *Merychippus*. The median cleft at the end of this phalanx is not so deep in *Neohipparion* as in *Merychippus*.

Comparative Skeletal Proportions in *Equus* and *Neohipparion*

Ratios	Modern Light Horse Average Thoroughbred	Neohipparion leptode No. 54 C.I.T.	Neohipparion whitneyi Measurements after Gidley No. 9815 A.M.N.H.
Scapula x 100/Humerus	113.9	108.6 ?	122.1
Scapula x 100/Radius	98.4	94.0 ?	94.7
Radius x 100/Humerus	115.7	115.6	129.0
Metacarpus x 100/Radius ...	67.5	84.8	87.8
Humerus x 100/Femur	74.9	73.8	74.5
Tibia x 100/Femur	90.8	101.4	113.7
Metatarsus x 100/Femur ...	68.4	80.4	100.0
Metatarsus x 100/Tibia	75.3	79.3	87.9

The ratios given above demonstrate that *Neohipparion* differs from *Equus* (average Thoroughbred) in the greater

elongation of the distal limb segments (radius, metacarpus, tibia, metatarsus) in relation to the proximal segments (humerus, femur). The limb bones of *Neohipparion whitneyi* show extreme cursorial adaptation. As Gidley (1903) has shown, the limb lengths of *N. whitneyi* conform much more closely with those of the Virginia deer *(Odocoileus virginianus)* than with those of *Equus caballus*. *N. leptode*, in this respect, differs less from *Equus caballus*.

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CRETACEOUS GLASSY WELDED TUFFS — LEWIS AND CLARK COUNTY, MONTANA

JULIAN D. BARKSDALE

ABSTRACT. Glassy rocks of Cretaceous age that megascopically would be classified as pitchstone porphyries are shown to be welded tuffs. The use of the terms *welded tuff* and *ignimbrite* is discussed.

INTRODUCTION

WHILE examining volcanic rocks in a large quarry, approximately one mile south of Wolf Creek and 35 miles north of Helena, Montana, on U. S. Highway 91, Professor Adolph Knopf in 1947 collected specimens of black glass which he identified in thin section as welded tuff or ignimbrite.

Professor Knopf, Mrs. Knopf, and the writer visited the locality in 1949, and the specimens on which this study is based were then collected.

The writer, who is studying welded tuffs from western Nevada, wishes to thank Professor and Mrs. Knopf for pointing out the Montana locality and for encouraging his recording of it. Thanks are also due to Mr. William Boulton for the photomicrographic work.

GEOLOGIC OCCURRENCE

Volcanic rocks which include the glassy welded tuff crop out in a belt about 2 miles wide, extending northwest and southeast of Wolf Creek, Montana, and are part of a group named by Lyons (1944, pp. 449, 459) the *Adel Mountain volcanics*. He describes them generally as

> ". . . . trachybasalt and basalt agglomerate, conglomerates and flows with numerous intrusives, analcime and augite trachybasalts in upper measures; contains plant fossils in upper conglomerates . . . ."

The thickness of the section is approximately 3,200 feet.

The southwestern boundary of the volcanics in this area is a mechanical one. A well-exposed thrust fault, striking N 35° W and dipping 20° to the south brings thinly bedded argillites of the late Precambrian Belt series over Adel Mountain volcanic rocks of Cretaceous age. The fault is probably the northern continuation of the Eldorado overthrust,

regarded by Pardee (1933, p. 130) as a subsidiary slice of the Lewis overthrust.

The glassy welded tuffs, which range in specific gravity from 2.33 to 2.355, occur in a layer from 5 to 6 feet thick, and are best exposed in a large quarry which lies several hundred feet below the projected fault surface. The rock in question has a conchoidal fracture and the luster of black pitchstone. There are small dull non-vitreous patches mottling some of the joint blocks of glass. In others, part of blocks several feet across show at first glance no glassy luster, but on closer examination sufficient unaltered glass can be found to identify the layer and permit its being traced across the quarry for several hundred feet. Fracturing and shearing below the thrust and irregular distribution of devitrification make megascopic distinction between the tuff and flow rocks impractical except where large artificial cuts have been made.

MICROSCOPIC DESCRIPTION

Thin sections of both the glassy and the dull black, apparently aphanitic, rocks were studied. Figure 1 of plate 1 is a photomicrograph of the former and figure 2 of the latter.

Both rocks are clearly seen to be of fragmental origin. Crystals and fragments of fresh labradorite (zoned An 59 to An 44), apatite, and magnetite together with rare fragments of very fine-grained porphyritic flow rocks, a few turbid brown outlines of altered ferromagnesian minerals, augite, hornblende, hypersthene, and a few fragments of secondary (?) epidote are embedded in a very compact matrix of bent and flattened, elongate fragments of glass, the index of which is >1.50, <1.505. This is the index of potash-rich glass, but no orthoclase or sanidine occurs in the slides examined. Most of the glass fragments have clear colorless rims surrounding amber to dark brown glass centers similar to fragments in the Yellowstone tuffs or collapsed pumice described

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PLATE 1

Fig. 1. Glassy welded tuff showing linear arrangement of fragments. Note bending of fragments around labradorite crystal. Near Wolf Creek, Montana.

Fig. 2. Partly devitrified welded tuff showing characteristic bending of fragments around crystals of labradorite. Near Wolf Creek, Montana.

FIGURE 1

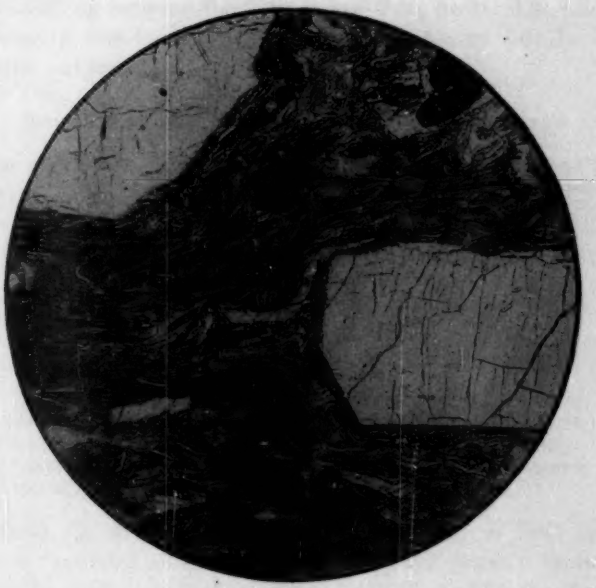
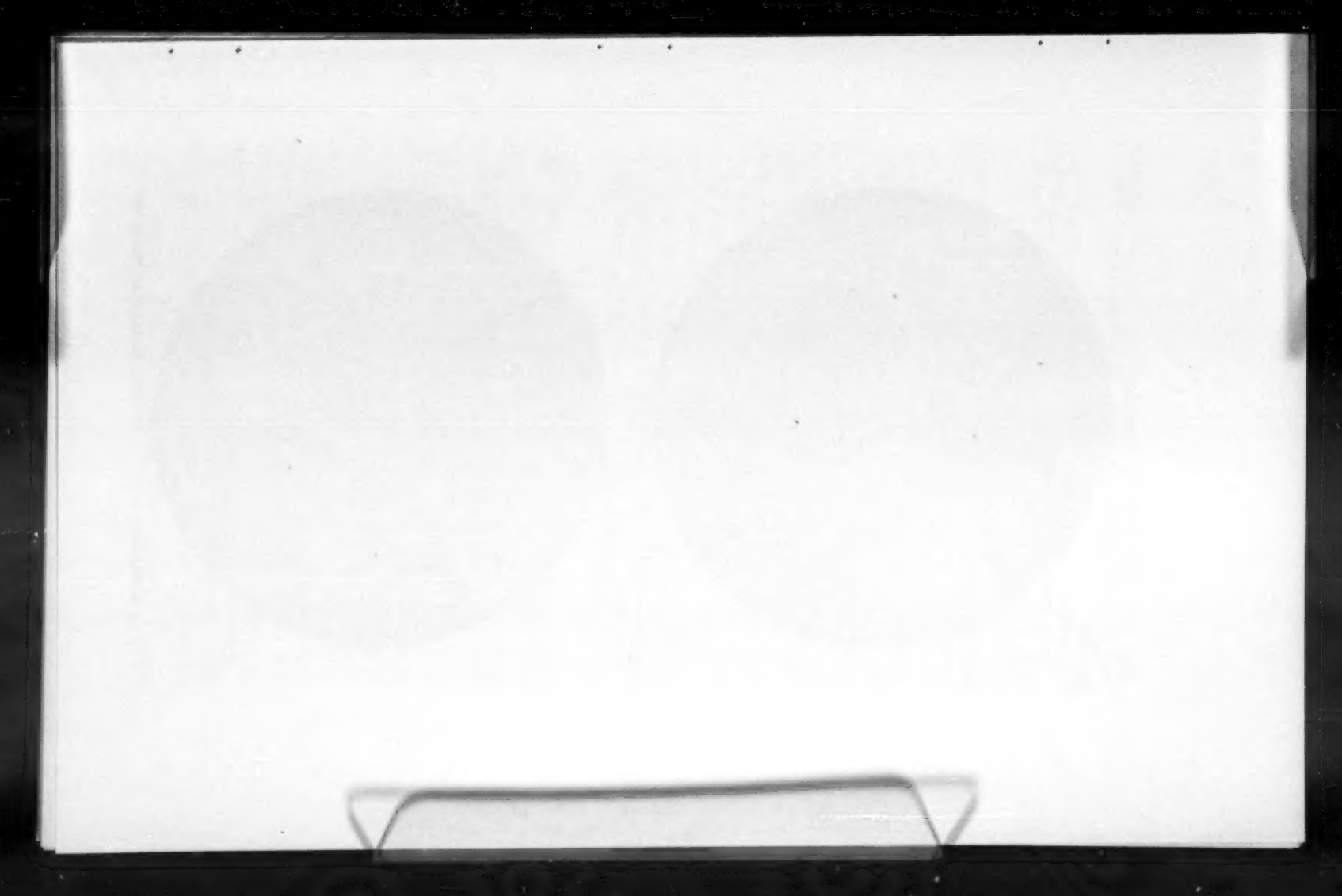


FIGURE 2



by Iddings (1899, pp. 404-406; 1909, pp. 331-332). Mansfield and Ross (1935, p. 317) noted similar occurrences in southeastern Idaho, and the writer has found the same type of occurrence in the welded tuffs in western Nevada. Some of the larger fragments are colorless throughout as illustrated by the large bent fragment in the center of plate 1, figure 1.

The glass fragments are molded around the solid feldspar crystal without breaking. This is taken as evidence that the fragments of glass were welded while still hot and viscous to form a solid rock. The curved cracks in the section have a perlitic pattern; individual glass fragments show no lateral displacement along these cracks.

There is no discernible devitrification of the glass fragments in the rocks illustrated by plate 1, figure 1, except along the perlitic cracks. Birefringence along the cracks causes the perlitic pattern to show up better under crossed nicols than in plain light. The dull aphanitic-appearing rock (plate 1, fig. 2), is essentially glass; but it has begun to devitrify since there is a faint birefringence in the finest particles and dustlike filling between the larger glass fragments. The perlitic cracking of this rock is also made noticeable by faintly birefringent outlines.

NOMENCLATURE AND AGE OF THE WELDED TUFFS

The rocks described are doubly interesting in that first they are true welded tuffs formed as Iddings (1909, p. 331-2) said

> ". . . . when exploded fragments of molten magma, large and small, fall together in a still heated condition . . . . they may be plastic enough to weld together into a more or less compact coherent mass."

The term *ignimbrite* was proposed by Marshall (1935, p. 323)

> ". . . . for rocks thought to have been deposited from immense clouds of showers of intensely heated but generally minute fragments of volcanic magma. The temperature of these fragments is thought to have been so high that they were viscous and adhered together after they reached the ground."

Marshall (p. 323) further qualifies the term in that ignimbrite is regarded as formed by an eruptive process similar in nature to that described by Fenner (1925, p. 198) at Katmai in the Valley of Ten Thousand Smokes, Alaska.

The term *ignimbrite* has not been generally used. Fenner (1948, p. 882-883) points out that deposits resulting from volcanic action similar to the Katmaian tuff-flow type are of several kinds. No one name will suffice.

Fenner (1948, p. 883), following the original usage of Iddings, would apply the term *welded tuff* to those deposits in which the heat of the accumulated mass is so high after emplacement that pumice inclusions collapse and the small fragments or shards of glass of the matrix become softened and are pressed down and aligned by the weight of the material above them to form a rock which megascopically may appear like a felsitic rhyolite or even a structureless obsidian. For those in which induration is primarily the result of recrystallization, and for those in which the fragments have little cohesion, another term is desirable. Fenner (1948, p. 883) has described such tuffs from the vicinity of Arequipa, Peru, using for them the local term *sillar*.

Secondly, a large proportion of the Wolf Creek welded tuffs have not been devitrified although they are of late Upper Cretaceous age. The basis for the age determination is a collection of fossil plants made by Lyons from conglomerates in the upper part of the Adel Mountain volcanics one mile north of Craig, Montana, and determined by Erling Dorf as indicating late Upper Cretaceous, probably Montana age (Lyons, 1944, p. 465).

Previously described occurrences of glassy welded tuffs—Iddings (1899, 1909), Fenner (1923), Mansfield and Ross (1935), Marshall (1935), Gilbert (1938), Williams (1942), Wilkinson (1950)—are all mid-Tertiary or younger in age. The oldest previously reported glassy welded tuffs are those described by Mackin and Nelson (1950) from the Iron Springs district of Utah. These rest conformably upon Pink Cliffs Wasatch (Eocene) sediments and have Wasatch-type sediments interbedded in the upper part of the volcanic sequence.

The undevitrified glass of the welded tuffs of the Adel Mountain volcanics of late Upper Cretaceous age is thought to be the oldest of its type so far recorded.

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A TYPE OF BOGHEAD COAL FROM ILLINOIS*

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ABSTRACT. A type of boghead coal from the Tradewater group (middle Pottsville) of Pennsylvanian age is reported from Fulton County, Illinois. This is the first reported occurrence of a type of boghead coal in the Eastern Interior Basin. It is not a true boghead coal because it contains a considerable amount of anthraxylon intermixed with algal colonies, which indicates a type of coal transitional toward normally banded coal.

INTRODUCTION

DEPOSITS of boghead coal are known from Alaska, Australia, France, Scotland, South Africa, and the United States. In the United States, three boghead coal deposits have been reported: Kiskiminetas Junction, Pennsylvania, of upper Allegheny age; Neshannock Creek near Leesburg, Pennsylvania, of upper Pottsville age; and Paintsville, Kentucky, of upper Pottsville age.

A column sample of coal was taken from a bed outcropping in the SW¼ sec. 34, T.6 N., R.1 E., Fulton County, Illinois. The bed exposed averaged 40 inches in thickness, and the top 2 to 2½ inches contained abundant algal remains. The coal below this top portion of the bed is normally banded bituminous coal. The bed is identified as the Tarter coal bed of the Tradewater group (middle Pottsville). This is the first report of the presence of algae in coal from the Eastern Interior Basin.

The nomenclature of coal beds containing algal remains is in a somewhat confused state. Numerous names have been applied to deposits of this type, but perhaps the two most commonly used are *boghead* and *torbanite*. Cadman (1948) states: "It is now generally accepted that a torbanite differs from coal so markedly that it must be regarded as a distinct class of mineral." Parks and O'Donnell (1948) have set up a type classification of coal consisting of five main types. Two of these five types are boghead and cannel coal. They

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are separated from the other three types by Parks and O'Donnell who consider these two types of coal to contain less than 5 per cent anthraxylon. Cannel coal is characterized as predominantly translucent attritus with few or no oil algae. Boghead coal is characterized by the translucent attritus being predominantly oil algae.

These qualifications for differentiating boghead from cannel coal are questioned by Schopf in a discussion which immediately follows the paper by Parks and O'Donnell. Schopf's questions, in part, arise from the fact that many cannel and known boghead coals could not qualify as such under the requirements of the type of classification. If a coal cannot be classified either as cannel or boghead coal, it does not mean that this coal can be appropriately classified into one of the three remaining types. Parks and O'Donnell suggest the use of subtype designations to distinguish varieties of coal that have mixed characteristics of the main types suggested. Schopf (1949) indicates the need for a more precise system of classification of all algal-bearing deposits.

DESCRIPTION AND DISCUSSION

Megascopic examination of a polished surface of coal of the type found in Illinois shows a rather dull luster with a considerable number of lenticular anthraxylon bands. These bands are very thin, the thickest not exceeding half a millimeter. A few scattered, thin, lenticular patches of fusain have been noted, as well as a small amount of pyrite.

Microscopic examination of thin sections revealed that this coal contains much more than 5 per cent anthraxylon. Considerable difficulty was encountered in attempting to measure the amount of the ingredients, due to the fact that the matrix consisted of interlaminated anthraxylon and opaque attritus. Many of the anthraxylon-like laminations were less than 14 microns thick, the lower limit for anthraxylon determination as established by the United States Bureau of Mines. Therefore these fibrous laminations (translucent humic degradation matter) less than 14 microns thick were classified as translucent attritus. An average of the percentage of the ingredients measured from a number of thin sections follows:

Anthraxylon		24%
Translucent attritus		
Translucent humic degradation matter	17%	
Algae	33	
Spores, resins and cuticle	5	
	55%	55
Opaque attritus and undifferentiated mineral matter		20
Fusain		1
		100%

Spores, cuticle, resins, and algal remains are clearly translucent even in thick sections, resulting in a tendency to halt the thin section preparation before proper thinness is attained. Thus on the first thin sections made, the total amount of anthraxylon was not clearly apparent. These sections suggested that the percentage of opaque attritus was high and that of anthraxylon was low. Sections of proper thinness showed the true proportion of anthraxylon in relation to those of the other ingredients. Sections of a Permian boghead coal from South Africa, in the collection of the Illinois Geological Survey, showed that anthraxylon is virtually lacking in it, and that its most abundant constituent is opaque attritus with a much smaller amount of algal remains. The percentage of the algae in this coal is comparable with that found in the Illinois coal.

It is apparent that because the African boghead contains less than 5 per cent anthraxylon, it can be classified by Bureau of Mines standards as a boghead coal, but the Illinois coal cannot be classified as a boghead coal because of the high anthraxylon content, despite the fact that both coals contain algae in about the same proportion. The coal from Illinois is considered to be a type of boghead coal because it contains the algal remains so characteristic of typical boghead coals. The presence of large amounts of anthraxylon is thought to show the interrelationship between normally banded bituminous coal and boghead coal. The Illinois type of boghead is not markedly different from coal and cannot be regarded as a distinct mineral as suggested by Cadman (1948).

The history of the study of boghead coals has been given

by Thiessen (1925), Blackburn and Temperley (1936), and others. The conclusion reached by Blackburn and Temperley, that all previously described algae from boghead coals are to be identified with the recent algae *Botryococcus Braunii* Kutz., is accepted by most workers. The specific differences in the fossil genera *Reinschia*, *Pila*, and the material identified as *Elaeophyton* by Thiessen are to be accounted for in colonial polymorphy. This would explain the considerable differences in the form of the colonies of the algae reported. *Botryococcus Braunii* is found, according to Smith (1933), only among the fresh-water plankton, and is widely distributed throughout the lakes of the United States, but is rarely abundant. It is also occasionally found in permanent or semipermanent pools.

Two questions of interest are: What were the environmental conditions favoring the development of the algae in Illinois at this particular time of the Pennsylvanian? and Where did they originate? With regard to their origin, nothing is known since this is the first reported occurrence of Pennsylvanian algae from a coal bed in Illinois. With regard to the environmental conditions, it would appear that arborescent plant growth was suppressed because large stems were not preserved in this part of the coal bed. The anthraxylon present is composed of very thin, lenticular bands. The fact that the algae are primarily restricted to the top portion of the coal bed suggests that they developed rapidly and existed briefly, thus accounting for the absence of thick bands of anthraxylon, or perhaps this type of coal represents a different type of accumulation.

Dulhunty (1944) believes that the Permian torbanites from New South Wales are composed of fossil algal remains closely related to *Botryococcus Braunii*. He explains the origin of the torbanite beds as a result of the development of isolated lakes. Water from the main channels, carrying dissolved and suspended mineral matter with some humic degradation products, entered these lakes by percolating through peat bogs, marshes, and sand beds. These lakes were alternately filled and emptied due to variations in the water level in the main channels, which prevented the establishment of either terrestrial or sub-aerial vegetation. The algae flourished under suitable conditions when the lakes were filled.

Figure 1 of plate 1 illustrates a characteristic portion of

the boghead type of coal, in vertical section, with numerous colonial algae (light-colored areas) in a matrix composed of many thin lenticular strands of translucent humic degradation matter and fibrous anthraxylon, and opaque attritus. One prominent band of anthraxylon (AN) crosses the entire length of the photomicrograph. Figure 2, a horizontal section, shows an anthraxylon lenticle which in this plane occupies the bottom half of the photomicrograph, with algal colonies in a matrix of opaque attritus above. *Laevigato-sporites* (L), a monolete small spore genus, shows through the anthraxylon from below. Figure 3, a horizontal section, illustrates an anthraxylon lenticle on the left, a portion of a megaspore coat (MG) on the right, and algal colonies in opaque attritus. Figure 4, a horizontal section, illustrates two adjacent algal colonies surrounded by opaque attritus. Figure 5, a vertical section, illustrates several algal colonies with one large colony near the top of the photomicrograph. Traces of individual cells may be distinguished. The matrix is opaque attritus. Figure 6, a vertical section of normal coal from the

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EXPLANATION OF PLATE 1

Fig. 1. Thin section vertical to bedding illustrating anthraxylon (AN), numerous algal colonies (light colored areas), fibrous anthraxylon, and translucent humic degradation matter. x245.

Fig. 2. Thin section horizontal to bedding with anthraxylon (AN) in the bottom half of the photomicrograph with opaque attritus above containing algal colonies. *Laevigato-sporites* (L), a monolete small spore genus, shows through the anthraxylon from below. Ultropak photomicrograph at about x146.

Fig. 3. Thin section horizontal to bedding illustrating anthraxylon (AN) with cellular structure to the left, a portion of a megaspore (MG) to the right, and opaque attritus with algal colonies in the middle. Ultropak photomicrograph at about x100.

Fig. 4. Two adjacent algal colonies from a horizontal thin section showing some traces of individual cells. Ultropak photomicrograph at about x320.

Fig. 5. Thin section of opaque attritus vertical to bedding with more or less longitudinal sections of algae. Traces of individual alga cells may be distinguished in the large colony near the top, and indicated by the dark pitted areas on the smaller colonies. Ultropak photomicrograph at about x320.

Fig. 6. Thin section vertical to bedding illustrating normally banded coal from the top third of the coal bed below the algal band. Near the top are two anthraxylon (AN) bands separated by opaque attritus. Below this is a splint layer with opaque attritus, some fibrous anthraxylon, spores, and cuticle. A portion of a megaspore (MG) is at the bottom. Ultropak photomicrograph at about x66.

AN
MG
AN
AN
MG

top third of the coal bed, shows two prominent bands of anthraxylon separated by opaque attritus. Below this is a splint layer of opaque attritus and numerous spores and cuticle. The anthraxylon in this splint portion is rather fibrous. A portion of a megaspore is shown near the basal portion of the photomicrograph.

The algae in this coal bed compare favorably with those described by Thiessen (1925) from Pennsylvania and Kentucky. Individual distinct alga cells are, for the most part, not prominent in the material examined. They are perhaps more clearly defined than those described by Thiessen, but not as clearly defined as in the boghead coal from Scotland. The question as to whether these algae are to be specifically identified with *Botryococcus Braunii* Kutz., as suggested by Blackburn and Temperley, has not been answered in the present study.

Some of the coal from Illinois was macerated in the hope that further information might be obtained from isolated algal colonies. After prolonged treatment in Schulze's solution, cuticle, some megaspores, and a few algal colonies were isolated. The individual colonies picked out of the maceration residue showed little or no resolvable structure, and appeared rather as irregular orange globular masses. The irregularity of these colonies made examination, except at low magnification, impossible because only a small portion of a colony lies in the same plane of focus.

CONCLUSION

The discovery of a type of boghead coal from Illinois records the presence of algae during coal deposition in the Eastern Interior Basin. The algae accumulated on the top of the peat bog in rather large numbers under fresh-water conditions prior to subsequent deposition of overlying sediments, and were preserved in the coal. The coal is perhaps not a true boghead coal because of rather large amounts of anthraxylon. The presence of anthraxylon intermixed with algal colonies indicates that this is a transitional type of coal suggesting a relationship with normally banded coal.

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QUANTITATIVE SPECTROCHEMICAL ANALYSIS OF RUBIDIUM IN LEPIDOLITE

(For geological age measurements by the strontium method)

L. H. AHRENS AND LORRAINE G. GORFINKLE[1]

ABSTRACT. Two spectrochemical procedures, both of which employ potassium as an internal standard are described for the quantitative analysis of rubidium in lepidolite. The standard deviation per single determination is about 2.5%.

INTRODUCTION

FOR the determination of geological age, the strontium method has been applied with reasonable success to lepidolite mica and in all some thirty age measurements have been made (Ahrens, 1949). Although these age measurements may for the most part be regarded as quantitative, they are not precision measurements and isotope analyses have not been made. Here, a method is described for the accurate analysis of rubidium in lepidolite; the accurate analysis of strontium and its concentration for isotope analysis, will be described later.

POTASSIUM AS AN INTERNAL STANDARD FOR RUBIDIUM

When using d.c. arc excitation for the analysis of an alkali metal, the greatest accuracy is usually attainable by employing another alkali metal as an internal standard. This holds particularly well for the pair Rb-K, and either element is an excellent internal standard for the other. If potassium is to be used as an internal standard in the usual way for the analysis of rubidium in lepidolite, its concentration should remain constant in this mineral. In lepidolite the potassium concentration does not remain constant, but the variation is relatively slight and is usually within about 5% of the mean K_2O concentration in lepidolite; see analyses by Stevens (1938) for example. For many determinations, this variation

[1] This investigation is part of a general program of spectrographic research carried on in the Dept. of Geology, M. I. T. under contract with the Office of Naval Research, Washington, D. C., and under the supervision of H. W. Fairbairn.

may be neglected, but for utmost precision cognizance would of course have to be taken of such a variation. In this paper, two methods are described, both of which use potassium as the internal standard; in one, K_2O is assumed constant and in the other allowance is made for possible significant variation in its concentration.

PREPARATION OF STANDARDS

To reduce systematic error as far as possible, the use of purely synthetic standards was avoided and standards were prepared by adding RbCl in known amount to a specimen of lepidolite (Southeast Manitoba). The added RbCl was first incorporated into a base of albite (National Bureau of Standards No. 99). In this albite, the rubidium concentration was determined as 0.0011% Rb_2O (analyst Miss M. Kearns) and as the concentration of rubidium in lepidolite averages at about 1.5%, albite rubidium does not interfere. The Southeast Manitoba lepidolite specimen itself, and all unknowns, are diluted with five parts of albite; all determinations are therefore made in an albite matrix.

A primary standard containing 10% RbCl in an albite matrix is first prepared (9 parts albite, 1 part RbCl). This is added to a specimen of lepidolite (diluted with 5 parts of albite) as follows:

(1) 1 part 10% RbCl standard to 9 parts albite-diluted lepidolite
(2) 1 part 10% RbCl standard to 19 parts albite-diluted lepidolite
(3) 1 part 10% RbCl standard to 39 parts albite-diluted lepidolite

Each of these three standards will contain 1%, 0.5% and 0.25%, respectively, of added RbCl.

Lepidolite contains about 10% K_2O and as the specimen of albite contains 0.41% K_2O, 5:1 dilution of lepidolite with albite reduces the K_2O content to 2.02%. In each of the addition standards K_2O will vary slightly; for (1), (2) and (3), % K_2O will be 1.86%, 1.94% and 2.02%, respectively. Adjustment to a constant K_2O concentration level (at 2.02%) is made by multiplying the intensity of the internal standard line of potassium by $2.02/x$, where $x = 1.84$ or 1.96.

OPERATING DETAILS

Plate type and developing procedure: Eastman 103-0, developed for five minutes in Kodak D-19 developer (diluted 1:1) at 70°F.

Electrodes: Carbon (purest grades not necessary), 3/16" (ext. dia.) x 1/8" (int. dia.) x 1/4" (cavity depth).

Excitation: d.c. arc; first five minutes at 3 amp.

Calibration: Self-calibration from stepped spectra, using sector steps which transmit 1/2, 1/4, 1/8 and 1/16 total radiation.

Analysis pair: K 4044 or 4047 (internal standard line) and Rb 4202 (analysis line). Excitation potentials, 3.05 and 2.94 volts, respectively.

Arc stabilization: none.

Comment on CN background: CN band with head at 4216 A quite frequently interferes with the above analysis lines, but using the operating conditions described here such interference is absent.

WORKING CURVES

Figure 1 shows a plot of %RbCl added versus the ratio I Rb 4202/I K 4044. Each plotted point is the mean of three determinations. The intercept of the extrapolated curve with the abscissa gives the % rubidium (expressed as RbCl) in the lepidolite, albite mixture. After correction for albite dilu-

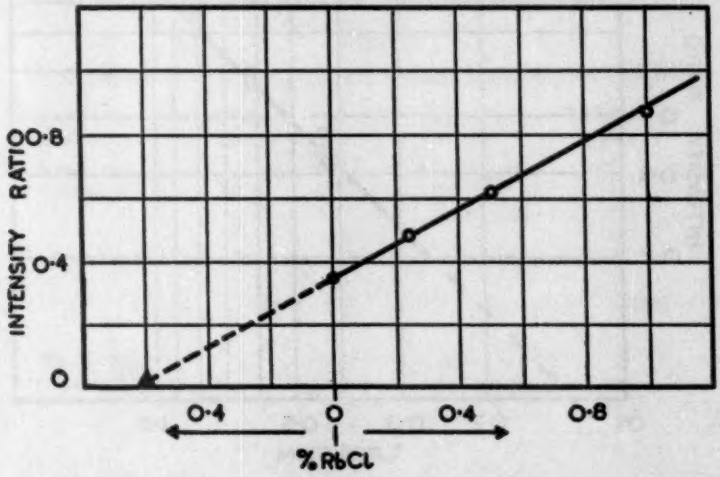

Fig. 1. Addition method of plotting for the determination of rubidium in lepidolite. ($\frac{\text{I Rb 4202}}{\text{I K 4047}}$ versus % RbCl added). Each specimen diluted with 5 parts of albite.

tion, the rubidium concentration in the lepidolite specimen from Manitoba is 2.64% Rb. Strassmann and Walling (1938) found 2.6% Rb in lepidolite of the same type from the same locality, using a chemical method of analysis.

If the 5% variation in the K_2O content of lepidolite is to be taken into account, an addition method of plotting (fig. 1) may be used for each specimen, as described above for the Southeast Manitoba specimen. Otherwise, the above data may be employed for the construction of a working curve in the usual way, because the total concentration of rubidium in each standard (including the Southeast Manitoba specimen) is now known. Figure 2 shows such a working curve and is a plot of % RbCl versus I Rb 4242/I K 4044, using log-log

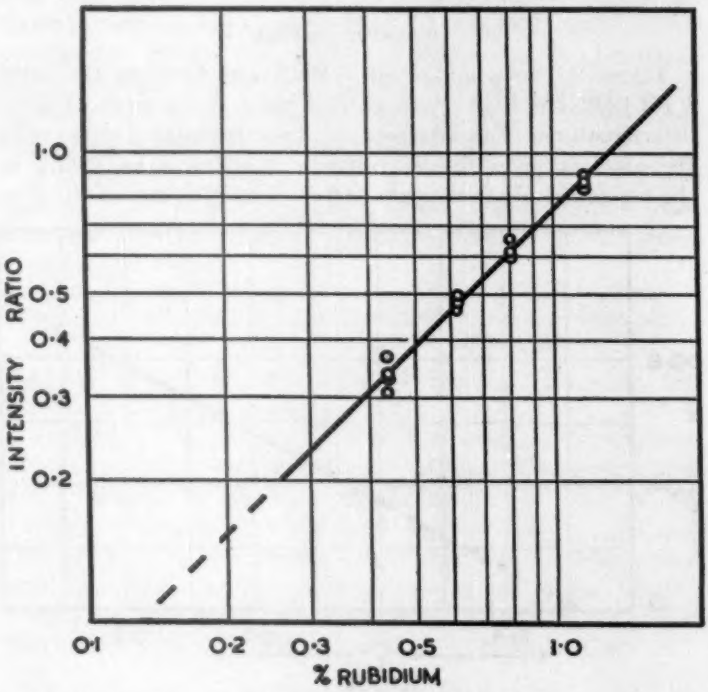

Fig. 2. Working curve for the analysis of rubidium in lepidolite ($\log \frac{\text{I Rb 4202}}{\text{I K 4047}}$ versus log % Rb). Each specimen diluted with 5 parts albite.

co-ordinates. This working curve appears normal in all respects; it has a unit slope. Actually, for the construction of such a working curve after first making the addition method plot, it would have been better to have used a specimen of lepidolite having a relatively low concentration of rubidium, namely, about 1%. All unknowns may then be determined within the working curve proper, and not on an extrapolated portion. In figure 2, however, the amount of extrapolation is not excessive.

REPRODUCIBILITY AND ACCURACY

Replicate analyses of several lepidolite specimens have been made and from such analyses the relative error (coefficient of variation, or standard deviation expressed percentagewise) has been calculated as 2.7%. This reproducibility is about as good as may be obtained by d.c. arc analysis and is due to excellent internal standardization of rubidium by potassium. Naturally, the fact that precision is high does not necessarily mean that the method is accurate. Systematic error could have arisen from the fact that in the standards added rubidium is as chloride, whereas in lepidolite, rubidium is within the silicate structure co-ordinated to oxygen. Such

TABLE 1

Replicate analyses of rubidium in some specimens of lepidolite

Locality	Analysis No.	%Rb	Locality	Analysis No.	%Rb
Varuträsk, Sweden	1	2.09	Winnipeg R. Southeast Man., Can.	1	2.56
	2	2.12		2	2.56
	3	2.13		3	2.60
	4	2.22		4	2.78
	5	2.14		5	2.65
	Mean	2.14		Mean	2.64*
Black Hills, South Dakota	1	1.56	Namaqualand, South Africa	1	1.26
	2	1.58		2	1.24
	3	1.53		3	1.34
	4	1.56		4	1.29
	5	1.47		5	1.21
	Mean	1.54		Mean	1.25

* This concentration of rubidium is about the maximum found in lepidolite, or in any other mineral.

an error appears to be absent, however, because in figure 1 the line of best fit for the three addition standards passes through the point for the lepidolite (no rubidium added). Had systematic error been present, this line would have been displaced with respect to the point for the lepidolite specimen.

Table 1 shows replicate analyses of four specimens of lepidolite.

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DISCUSSION

KYANITE PSEUDOMORPHS AFTER ANDALUSITE FROM DELAWARE COUNTY, PENNSYLVANIA

There are numerous references to the finding of andalusite in central Delaware County, Pennsylvania. The original reference to which all subsequent references ultimately turn is that of Edward S. Dana (1872, p. 473). Samuel Gordon (1922, p. 90) quotes figures telling of the finding of large nodules of andalusite crystals measuring up to 6 x 23 cm. and groups up to 60 pounds. He also refers to the article by Dana and includes two sketches of the andalusite crystal described by Dana. On comparing the drawings in the original and the drawings in Gordon's Mineralogy one discovers that the Gordon drawings are idealized drawings of the idealized drawing made by Dana! The "remarkable crystal of andalusite from Upper Providence, Delaware Co., Penna.," presents an irregularity in the number of faces amounting to hemihedrism, and the angles do not accord too closely with those of andalusite. Dana, blaming the irregularities on "an accidental irregularity", drew the crystal as it actually was, and then made an idealized drawing showing how it should be with all the faces present. No optical work was done.

It is very strange that in the course of some 87 heavy mineral separations performed on specimens of the Wissahickon formation from central Delaware County, many of them from areas sighted as andalusite localities, not even a microscopic trace of andalusite was found in the heavy fractions.

A nodule of prismatic "andalusite" crystals weighing approximately 10 pounds was found by the writer during the course of sampling central Delaware County. This nodule is now in the collection at Bryn Mawr College. A fragment of one of the crystals was examined optically and was found to be kyanite. A. W. Postel (1940, p. 123) mentions that there seemed to be a skin of kyanite on some of these nodules, but went no further.

More recently the writer found a nodule of granular quartz near Swarthmore (one of the localities mentioned in Gordon's Mineralogy) from which he was able to get five individual prismatic crystals, the largest one 3.5 cm. by 0.9 cm. Two oriented thin sections were made from one of the smaller crystals. One section was made normal to the length of the prism, the other parallel to the length of the crystal. The material is kyanite throughout. The kyanite is in fine prismatic crystals mostly oriented parallel to the length of the prism. A crushed specimen was examined for optical properties and cleavage. The angle between cleavage {010} and cross parting

{001} is 85°. The optical properties are entirely in accord with those given for kyanite in any descriptive mineralogy.

The specific gravity was difficult to measure because of unavoidable contamination by muscovite which coats the surfaces of the crystals. The result finally obtained was 3.36; low for kyanite, but decidedly too high for andalusite. The color on cleaned surfaces is blue.

The crystals are rather rough and the faces dull and iron stained. Although all the crystals have the same general appearance none of them give the same set of readings. The interfacial angles are of the order of those for kyanite, but the crystals are badly distorted (Dana's "accidental irregularities").

Andalusite is described as an antistress mineral, one which is produced by pure thermal metamorphism. Kyanite, on the other hand, is a stress mineral, one which is formed under conditions of regional metamorphism, high temperatures and pressures. The crystals most recently found suggest the following origin and history of the crystals:

The andalusite was formed by the contact of a hot mass of magma (a diabasic sill or flow) with the highly aluminous shale of the original sediments of the Wissahickon formation. Andalusite crystals were formed in quartz sand lenses in the shale. Later the region was subjected to regional metamorphism and the andalusite altered to kyanite by pressure. The argument has been raised that during the metamorphism of the region the crystal forms should have been distorted by the pressure, and that no distortion seems to have taken place. Dana's measurements and the measurements of the writer (measurements so variable as not to warrant publication) indicate very considerable distortion of the crystal form, and even an attempt by the material to attain to the external form of kyanite.

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ESSAY REVIEWS

The AMERICAN JOURNAL OF SCIENCE will hereafter use the separate heading Essay Reviews for those longer discussions of recent literature that go beyond the span and scope of an ordinary review. It is hoped by means of such essay reviews to call the attention of the American geological profession to significant new and unfamiliar ideas appearing in publications that might otherwise escape the attention they deserve, and also to explore the implications of such ideas. The Editors will be pleased to receive and consider contributions of this sort for publication in the JOURNAL.

Logical Foundations of Probability; by RUDOLF CARNAP. Pp. xvii, 607. Chicago, 1950 (The University of Chicago Press, $12.50).—Carnap's book is a contribution of first magnitude both to the theory of probability and to the wider field of scientific methodology. Its scope is enormous, its workmanship impressive in all respects. To say that it is factual and uninspired is to praise it, for there are altogether too many books that ride appealing mathematical and philosophic hobbies, carrying to their readers messages that seem inspired but that fall to pieces on analysis. The present volume is solid logical research.

For the sake of rough classification, writers on the foundations of probability can be assigned to two camps for which I shall employ the labels *empiricist* and *logicist*. The empiricists hold that probability is some measure of objective credibility which is in principle verifiable by observations, although verification may often be difficult. The logicists regard it as a quality of sets of propositions, or, to use Carnap's simple version, of sentences, namely their quality of being reliable. Measurement of this quality may be impossible; if a numerical value is assignable this must somehow be in accord with the intuitive expectation that the sentence shall be true.

Empiricists usually employ as a measure of their probabilities the relative frequency of the events in question, while the logicists are less unanimous in the selection of bases upon which the assignment of numerical values for their probabilities can be founded. Some, indeed, have disavowed the need for associating numbers with probabilities altogether and have taken them to be subjective expressions for the intensity of their beliefs.

Carnap wishes to effect a reconciliation between these camps. He recognizes the current use of two different ideas under the name of probability and proposes to distinguish them with care: probability$_1$ and probability$_2$. The latter is the empiricist's stock

in trade; the former belongs to the logicist. P_2 is not very problematic; it has been illuminated and satisfactorily formalized by earlier investigators and requires no further comment in the present context. The book intends no positive contribution to our understanding of P_2. But P_1 is studied with greater thoroughness than has ever been done before.

It is defined as "strength of confirmation" of an hypothesis relative to available evidence. A scientific theory, for instance, is taken as the hypothesis, and known instances of proof or disproof constitute the evidence for its degree of confirmation. Through this definition P_1 becomes an aspect of a problem of much wider scope: it becomes the index of validity for an *inductive inference* and thereby turns into an element of a rather undeveloped field, called inductive logic. This is in fact Carnap's strongest claim, a point which he argues with great insistence. Because of the enlargement of the field of view resulting from the recognition that P_1 is peculiar to every inductive inference, Carnap's book is a treatise on inductive logic as well as on probability.

Deductive logic argues from premises and arrives at certain conclusions if the premises are true. Inductive logic surveys an empirical situation and formulates propositions extending the range of that situation, but almost never with certainty. The rules for the latter procedure have often been discussed, but perhaps never with the cogency and clarity of Carnap's treatise. Whether his interpretation of probability is satisfactory or not, the book is a monumental contribution to inductive logic.

In my opinion Professor Carnap, like most specialists, overestimates the applicability of his tool. He often writes as though scientists wanted very much to know the degree of confirmation, if possible in numerical form, of their theories in view of observational evidence. His examples suggest that he regards this as a burning question. He himself does not attack it in detail, but his moderation is caused by the belief that the evidential situation is too complex for treatment at the present time. Speaking of relativity and the quantum theory, Carnap says that "the structure of the new physical theory in each of these cases is so comprehensive and complicated that no physicist at any stage of the development has given a complete and exact formulation of it (according to the rigorous standards of modern logic), let alone a complete and exact formulation of the observational evidence. Therefore an application of inductive logic in these cases is out of the question." (p. 243)

I doubt if a theory of relativity, like Einstein's, or a specific quantum theory, like Schrödinger's will ever be formulated more completely or more exactly. Doubtless they will undergo modifica-

tion when better experimental evidence becomes available. Clearly, if such theories have a defect, it is not a lack of exact formulation or of complete statement; it is their failure to conform exactly with the facts. I am quite convinced that no amount of logical explication could render a better, or more complete account of the quantum theory (or at least one form of it) than Schrödinger's equation, together with a definition of its symbols and a statement of boundary conditions, and this is indeed the customary formulation. And as to an exact presentation of the observational evidence, this seems to be a very artificial demand, hardly capable of being satisfied because of the innumerable instances of use wherein the validity of Schrödinger's theory is taken as a premise or is implied. The physicist will see no sense in the construction of a catalog of all evidence to please the logician. But should he?

Certainly he should—if his science were a branch of inductive logic. The reason why most men working in the exacter sciences seem ill at ease when confronting this situation is that they regard themselves not as inductive logicians, but as constructive theorists. They take an equation like Schrödinger's as a postulate, derive its "L—implicates" (to use Carnap's terminology) i.e. its consequences, and test these against observations. If the test fails they modify the postulates. This involves the methods of deductive logic as they take special form in mathematics; inductive reasoning is used only in the adjustment of observations. From this point of view some of Carnap's prescriptions and examples sound strange, and it becomes clear why scientists persist in their failure to provide what Carnap calls a complete and exact formulation of the observational evidence. But if only *one* fact significantly contradicts a theory they make much of it, for it alone suffices to enforce a modification of postulates. There is a very trenchant sense in which theories are "right or wrong," a sense which surpasses the assignment of shadowy degrees of confirmation.

This criticism, however, is not a sweeping one. It applies only to the so-called theoretical sciences. In others, *e.g.* the social and biological sciences, where correlational procedures predominate, inductive methods are very widely employed. Here Carnap's logic will be found highly fruitful. It seems to me as if all sciences pass through an early correlational or classifying stage before they become primarily deductive. Inductive reasoning marks these early stages, but finally gives way to the more definite and clinching processes of deduction. Carnap's book seems well designed to shorten the youth of a budding science.

As we have already emphasized, the treatment of the logical idea of "degree of confirmation" in this volume commands respect. But I do not believe that the use of probability in science, when

differing from P_2, is restricted to Carnap's version. All of these have one feature in common: they arise from special theories—physical, mathematical or otherwise—but assert that, when *translated into terms of relative frequencies* our experience will bear them out. For instance, the probabilities conveyed by a Gibbsian ensemble are logically quite different from the squares of the Schrödinger amplitudes, and both are different from Carnap's degree of confirmation. Yet they are probabilities in the truest sense of the word as physicists use it. In isolation, each of these P's (which as we have seen is neither P_1 nor P_2) is a construct, interesting from a mathematical point of view, and otherwise sterile. But they are not used in isolation, for each of them proclaims: interpret me in terms of relative frequencies and see what happens! It is successful verification which leads us ultimately to regard such mathematical constructs as probabilities. And Carnap's P_1, I believe, is one of them.

He, himself, stops short of this conclusion, though not very far from it. He regards P_1 as a "guide to life," as a "fair betting quotient," as "an estimate of relative frequency" and thereby seems to admit the existence of certain rules of correspondence which link P_1, abstractly defined, with P_2. This would seem to indicate the existence of two general kinds of probability concepts, to be sure, P_2 and something else. Of this latter class, P_1 is one representative among many. Be it said, however, that it is an extremely interesting one, and one about which a book like Carnap's needed to be written.

HENRY MARGENAU

The Geology of Indonesia; by R. W. VAN BEMMELEN. 2 vols. and portfolio of plates; pp. 1092, 430 figs., 180 tables. The Hague, 1949 (Government Printing Office; agents, Martinus Nijhoff, 60 guilders, appr. $16.00).—This immense work is the climax of a century of geological investigation in Indonesia and summarizes the results of that investigation. Just as the work approached completion in 1942, its author, R. W. van Bemmelen, became a prisoner of war, and after the war he had to recreate the entire work anew. Geologists all over the world will be grateful to him and to the Bureau of Mines and Geological Survey of the Netherlands Indies for carrying the project through after such setbacks and disappointments.

The main body of the work is Volume IA, General Geology, 756 pages of royal quarto. An accompanying portfolio (Volume IB) contains a pamphlet giving 32 pages of references, lists of figures and tables, and a full index, as well as 41 large sheets on which are printed 83 of the 378 figures, in general those that would not fit on the regular pages. Volume II, Economic Geology, is a more

modest volume of 276 quarto pages, containing its own figures, references, and index.

The scope of the work is in keeping with its bulk. Recognizing that geological provinces do not necessarily correspond to political boundaries, van Bemmelen has covered not only the political unit Indonesia but also the Andaman and Nicobar Islands, Malaya, British Borneo, the Philippines, Australian New Guinea, Portuguese Timor, and Christmas Island, and has turned also to pertinent material concerning Burma, Indo-China, South China, and Australia where it bears on the central issue, the general geology and geologic history of the East Indies region. Likewise, though the main emphasis is on "areal geology," no important facet of geology is ignored.

The volume on general geology is divided into six chapters. Chapter I, Physiography (59 pages), is a fine summary of the archipelago, as much structural as physiographic, which is fitting perhaps for a region tectonically so active. Excellent "physiographic" diagrams are presented for the main islands and groups, though unhappily they are scattered between this chapter and Chapter V. In Chapter II, stratigraphy (128 pages), van Bemmelen has in large part restricted himself to advances in stratigraphic knowledge since the publication of Rutten's older stratigraphic summary (Rutten, L. M. R., 1927. Voordrachten over de geologie van Nederlandsch Oost-Indië. Wolters U. M., Groningen—The Hague). The material given is therefore not complete and much of it is very detailed; for the most part its significance does not appear until Chapter V, to which in fact it serves as footnote or appendix material (though not adequately cross-referenced). Embedded in this chapter, however (pp. 79-103), is a superb discussion of the principles of stratigraphic correlation in the Cenozoic of the East Indies, including a section on the letter classification of the Tertiary by Rutten and a section on vertebrate stratigraphy by von Koenigswald. This discussion, in which the various kinds of paleontological and other evidence for correlation are described and compared, is one of the most valuable parts of the book and should receive wide general attention.

Chapter III, Volcanism, opens with a fine account of the active volcanoes in the Archipelago (86 pages), including the products of eruption, the types of activity, and the variety of forms produced. It will be of great interest to volcanologists. The rest of the chapter (33 pages) is devoted to a more general and theoretical discussion of igneous activity, based on the author's tectonic theories, of which more anon. Chapter IV, Geophysics (41 pages), likewise combines description of the seismic, gravimetric, and magnetic data with theoretical interpretation.

The meat of the book lies in Chapter V, Geological Evolution of the Physiographic Units (425 pages), which presents the geology and geologic history area by area. The statement of the geologic data leaves little to be desired; the pertinent literature has been compiled, digested, and where possible reconciled, and a lucid summary of existing knowledge in each area is presented. Original maps and sections are reproduced in great numbers, and many long literal quotations, some from otherwise unpublished oil company reports, are given. Were there nothing else in the book, the geological profession would be deeply indebted to van Bemmelen for making available in so compact a form so much geological material on one of the most interesting and significant regions on Earth.

But there is much else in the book. Van Bemmelen says (p. 728, in the short concluding chapter, The Geological Evolution of the Indian Archipelago) "It is evident that its (Indonesia's) geological history cannot be adequately told without a working hypothesis on the geological evolution of the entire earth." Such a working hypothesis he developed, as far back as 1931, in his Undation theory, "a completion of Haarmann's Oscillation theory," and this he has applied with sublime confidence, not to say a sense of mission, to the complex data of the Indonesian region, always finding an answer to each complexity in some ingenious development of the theory. The theoretical discussions are carried along *pari passu* with the geological descriptions throughout the central chapters; indeed in Chapter V the presentation of the data is interrupted not less than 22 times to present a series of schematic sections and an integrated summary of the geological evolution of a part of the region according to the theory. The author has attempted to separate data and theory by the device of using fine print for the latter, and, though occasionally his enthusiasm for his theory boils over into the large print as well, no reader will have difficulty in distinguishing the two. Indeed it is curious to observe how some doubtful conclusion from the data, stated dispassionately and with all proper qualifications in the descriptive section, may be subtly transmuted in the theoretical section into solid evidence for a major tectonic event demanded by the theory. Yet no harm is done, for the basic data remain available for all who wish them.

According to the Undation theory, all supposed evidences of tangential compression are the result of secondary gravitational sliding on the flanks of primary, vertical uplifts and depressions. Some of the most impressive descriptions in the book are those of the great landslide phenomena on the flanks of certain of the large Java volcanoes, such as Merapi and Lawu, whose cones are built on a foundation of weak late Cenozoic clay and marl. The association of unmistakeable slump scars near the crests of the volcanoes

with typical if small scale "tectonic" folding tens of miles distant around their feet seems to enforce the concept that gravity has been the cause. It is easy to see how, from such observations, van Bemmelen has come to ascribe all tectonic folding and thrusting, including the great nappes of Sumatra and Timor, to gravity, and perhaps it is a little ungracious to remark that many geologists will nevertheless refuse to follow the extrapolation. For van Bemmelen exhibits the common weakness of the school, that of stressing mechanisms that seem possible qualitatively without checking them quantitatively. Thus the cross-sections of the volcanoes in question are carefully drawn with equal vertical and horizontal scales, but the 22 series of schematic cross-sections, intended to be the theoretical climax of the book, as well as the diagrams illustrating the leading principles of the theory, are all drawn with not less than fourfold vertical exaggeration.

The same kind of criticism might be levelled at that portion of the theory concerned with the primary vertical movements of which the horizontal movements are but secondary results. Thus "van Bemmelen's physico-chemical hypothesis" to explain mountain roots and negative gravity anomalies (Chapter IV) depends on assuming "exothermic chemical reactions and changes in density" or "complex crystallization differentiation," but does not tackle quantitatively the problems of what reactions, what changes, what differentiation would produce the supposed results. Similarly the assumption that continental blocks ("borderlands") can founder to oceanic depths by being weighted down with basalt intrusions and extrusions seems quantitatively at odds with the principle of isostasy to which, like Haarmann, van Bemmelen pays lip service. Indeed among the remarkable features of the applications of the theory made in this book are the ease with which large crustal blocks are transported up and down (the Makassar strait, we are told, descended from a position above sea level to its present 6,000 to 8,000 feet below in the younger Quaternary) and the detailed geologic histories that are postulated for some submerged areas, such as the central Banda Sea, on the basis of theoretical demands and a few irregularities on the sea floor. Hypotheses built on such slender foundations are especially liable to disruption by even small additions of data. Thus the extension of the borderland Melanesia from the shelf north of New Guinea northward past the eastern Caroline Islands is based chiefly if not entirely (theoretical considerations aside) on a report of continental crystalline schist on Truk (p. 56); now that that report has been disproved, the alleged borderland evaporates, and the area is seen to belong to the Inner Pacific basin.

The Geology of Indonesia contains then not only an excellent description of that geology but a thorough working out of the theory

which, van Bemmelen firmly believes, alone can explain it. The student of tectonics will certainly want to study the evidence here marshalled, even if, like the present reviewer, he thinks that the theory contains too many *ad hoc* hypotheses and too much qualitative extrapolation to be wholly convincing. Such a reader, the reviewer suggests, would do well to jump from Chapter I directly to the regional descriptions of Java and Sumatra in Chapter V, where the most convincing evidence of gravitational sliding is adduced, and then turn either to other applications of the theory to specific regions, such as Borneo, the Banda Sea, and Timor, or to the more generalized statements of the theory in Chapters III and IV.

JOHN RODGERS

REVIEWS

Static and Dynamic Electricity, 2nd ed.; by W. R. SMYTHE. Pp. xxi, 616. New York, 1950 (McGraw-Hill Book Company, $8.50).—This book is the second edition of a well-known text. The general tenor of the book is unchanged though much new material is added.

The most readily apparent change is the introduction of rationalized m.k.s. units throughout. The nomenclature has been modernized with such changes as "condenser" to "capacitor" and "electromotive force" to "electromotance." The section on electromagnetic waves has been expanded, and material on the boundary value problems encountered in microwave work has been added. Many additional problems of greater than average difficulty serve as extensions of the text. Both text and problems contain material which has not previously appeared in the literature.

D. E. HARRISON, JR.

Measuring Our Universe; by OLIVER JUSTIN LEE. Pp. x, 170; 29 figs., 16 plates. A volume in the Humanizing Science Series. New York, 1950 (The Ronald Press Company, $3.00).—Professor Lee gives the popular reader a connected account of the measurement of distances "from within the atom to outer space." He treats successively units of length, calibration of the meter in terms of spectral wavelengths, geodetic measurements, and the distances of the sun, stars and other galaxies.

This is an admirable program, for its skillful presentation would afford the lay reader a clear insight into the logically interlocking structure of physical science. The execution of this program has been very uneven, however. Professor Lee is a recognized authority on the trigonometric parallaxes of the stars, and deals with this

topic admirably. He has written a chapter on measuring engines that can be read with profit by physicists and astronomers. But there are serious defects in the book. The layman will look in vain for some account of the dimensions of the earth, or modern information on the size and shape of our Galaxy; and he will not easily understand how the distances of other galaxies are determined. It is surprising that Hubble's name has not been mentioned in this last connection. A further omission is the important effect of absorption of light by interstellar matter upon the indirect methods of determining stellar distances.

There are a very few minor errors of fact. On p. 125 Magellan is incorrectly said to have been the first to describe the Magellanic clouds. On the following page Barnard's statement that cluster-type variable stars can be used as timekeepers to detect changes in the earth's rotation period is repeated; actually, most well-observed variables of this type show unpredictable deviations from strict periodicity which unfit them for such a purpose.

The art of enlivening a popular scientific book with apt quotation and metaphor is a difficult one and consequently not all readers will be attracted by the literary style of this work.

JOSEPH ASHBROOK

Das Polarisationsmikroskop; by C. Burri. Pp. 308; 168 figs., 4 plates. Basel, 1950 (Verlag Birkhäuser, paper cover, 28.80 Swiss francs; cloth bound, 32.80).—This book contains nine main parts, as follows: 1, The nature of light; 2, The microscope; 3, Studies in unpolarized light; 4, Microscopic study methods; 5, Pleochroism; 6, Conoscopic study methods; 7, Measurements of refringence by immersion methods; 8, Universal stage methods; 9, Construction and calculation of extinction planes of certain faces and zones of biaxial crystals. These titles indicate the contents of the book in summary fashion. It is worthy of note that in general the treatment of each subject begins with a brief summary of its historical development and includes a clear statement of the latest developments. The text is well written, systematic and accurate, but in some parts, notably the first and last, it is so largely mathematical in treatment that it is difficult reading for the average student.

A. N. WINCHELL

This Earth of Ours—Past and Present; by Caleb Wroe Wolfe. Pp. x, 374; 239 figs. Revere, Mass., 1950 (The Earth Science Publishing Company, $5.00).—Invading an already crowded field, this new book is aimed at the beginning student of geology and is particularly appropriate, according to the publishers, in a first year Liberal Arts course for the student who does not intend to major in geology.

The reviewer is unsympathetic with the avowed purpose because he knows that many liberal arts students with no career ideas in mind, become fired with interest in geology as a result of the first college course in it and subsequently make a career of it. Many more major in geology for its broad cultural value who scarcely knew what the word meant when they signed up for the first course. However, any new book in beginning geology deserves appraisal as to whether it 1) presents new data, 2) offers a truly new approach to an old subject or 3) just follows tradition but is clearer and more polished in execution than its predecessors. The reviewer does not believe that *This Earth of Ours—Past and Present succeeds* in any of these three respects.

Professor Wolfe definitely introduces more controversial discussion than is customary in beginning texts. Theories, for example, of glacial climates, causes of mountain building, origin of the earth, origin of life on earth, and evolution are treated briefly and simply. The author endeavors to set facts apart from speculation, but in short digests of such complicated and far-reaching problems a philosophical argument alone may confuse the inquiring student more than enlighten him. Dr. Wolfe employs an informal style, the editorial we, and not infrequently the question and answer method. The value of these devices to the student is not clear, especially in cases like the following excerpts from the concluding chapter Advice from Mother Earth:—

> "Man recognizes that he stands now upon the peak of evolution . . . . But man, as a race, has little claim to great distinction. Unless he reads well the lessons of geology, his path may readily lead down a blind alley . . . . What will the future hold? Man holds the answer locked within himself. It is to be hoped that a better man will inherit the earth of tomorrow, but the future does not look too bright . . . . . .
> Be fruitful and multiply!"

The book is unfortunately marred by errors, amateurish drawings, and poor reproduction of both line cuts and half-tones.

Line drawings are crudely done; lettering is without guides, and even where a previously published figure is "copied" (fig. 15.3) the result is almost illegible. Line drawings of animals and plants are without information as to size or scale. Quality of reproduction of half-tones is so poor that even famous, previously published photographs suffer loss of definition.

This Earth of Ours—Past and Present does not approach the postwar excellence of other available books intended for beginning geology students.

JOHN B. LUCKE

The Physical Basis of Mind. A Symposium; edited by PETER LASLETT. Pp. viii, 79. Oxford and New York, 1950 (Basil Blackwell; The Macmillan Company, $1.00).—This small book represents a series of talks, delivered over the BBC Third Programme, on what is probably at once the most central and the most difficult problem of science and philosophy. Seven scientists (Sherrington, Adrian, LeGros Clark, Zuckerman, Slater, Brain and Penfield) and three philosophers (Viscount Samuel, Ayer and Ryle) participated in the talks, which as presented here are superbly intelligible, honest and challenging.

The book is well worth reading by all who are interested in the problem because of its lucid statements of the positions maintained by these eminent authorities. But further than this, the fact that BBC sees its way to encouraging such interest by presenting to the general public evidences and opinions on such an abstruse subject as this deserves to be called to the attention both of American radio producers and American radio audiences, who might well raise their standards in emulation. JANE OPPENHEIMER

PUBLICATIONS RECENTLY RECEIVED

Geological Survey Professional Papers, as follows: 216, Structural Geology of the Hawthorne and Tonopah Quadrangles, Nevada; by H. G. Ferguson and S. W. Muller—$2.00; 219, Geology and Ore Deposits of the La Plata District Colorado; by E. B. Eckel and others—$2.50; 227, Pegmatite Investigations in Colorado, Wyoming, and Utah 1942-1944; by J. B. Hanley, E. W. Heinrich, and L. R. Page—$1.50,—Washington, 1949, 1950.

An Introduction to Probability Theory and Its Applications; by William Feller. New York, 1950 (John Wiley & Sons, Inc., $6.00).

The Nutritional Improvement of Life; by H. C. Sherman. New York, 1950 (Columbia University Press, $3.75).

The Carboniferous Rocks of the Llano Region of Central Texas; by F. B. Plummer. University of Texas Publication 4329. Austin, 1950 (University of Texas, paper cover $2.00, cloth bound $3.00).

The Geology of Indonesia; by R. W. Van Bemmelen. Vol. IA, General Geology of Indonesia and Adjacent Archipelagoes; Vol. IB, Portfolio of maps; Vol. II, Economic Geology of Indonesia. The Hague, 1949 (Martinus Nijhoff, 60 guilders).

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OBITUARY

Dr. Peter Marshall of New Zealand was born in England in 1869, and died in November 1950 at the age of 82. He graduated from the University of New Zealand in 1892 and received his degree of D.Sc. in 1901. He was lecturer and later Professor in charge of geology in the University of Otago, Dunedin, New Zealand. On several occasions he held fellowships of the Bishop Museum, Yale University for geologic studies in the various Pacific islands. In New Zealand his studies were largely of volcanic rocks. Earlier studies were of alkalic rocks, but in 1935 he published in the Transactions of the Royal Society of New Zealand a paper on "Acid Rocks of the Taupo-Rotorua Volcanic District". This is the work for which Dr. Marshall is best known in America, for it was a fundamental contribution to an understanding of the type of volcanic eruption exemplified by Pelee and Katmai. He proposed the name ignimbrites, commonly called welded tuffs in this country, for the products of these eruptions.

Dr. Marshall's studies of the volcanic rocks in the islands of the western Pacific led him to conclude that a line dividing regions characterized by andesitic rocks from those containing alkalic ones coincided with significant tectonic features, and constituted the structural margin of the western portion of the Pacific. For their marginal line he proposed the term the "andesitic line".

Geologists from other countries who had opportunities of meeting Dr. Marshall at two meetings of the International Geologic Congress, and at several meetings of the Pacific Science Congress; had the pleasure of establishing firm friendship with the man whose work they had long admired.

CLARENCE S. ROSS
U. S. Geological Survey
Washington, D.C.

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